LA-UR-16-24221

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Title:	Los Alamos and the Neutrino: 60 years of discovery
Author(s):	Rielage, Keith Robert
Intended for:	Physics/Theory Colloquium and for historical record
Issued:	2017-05-08 (rev.1)

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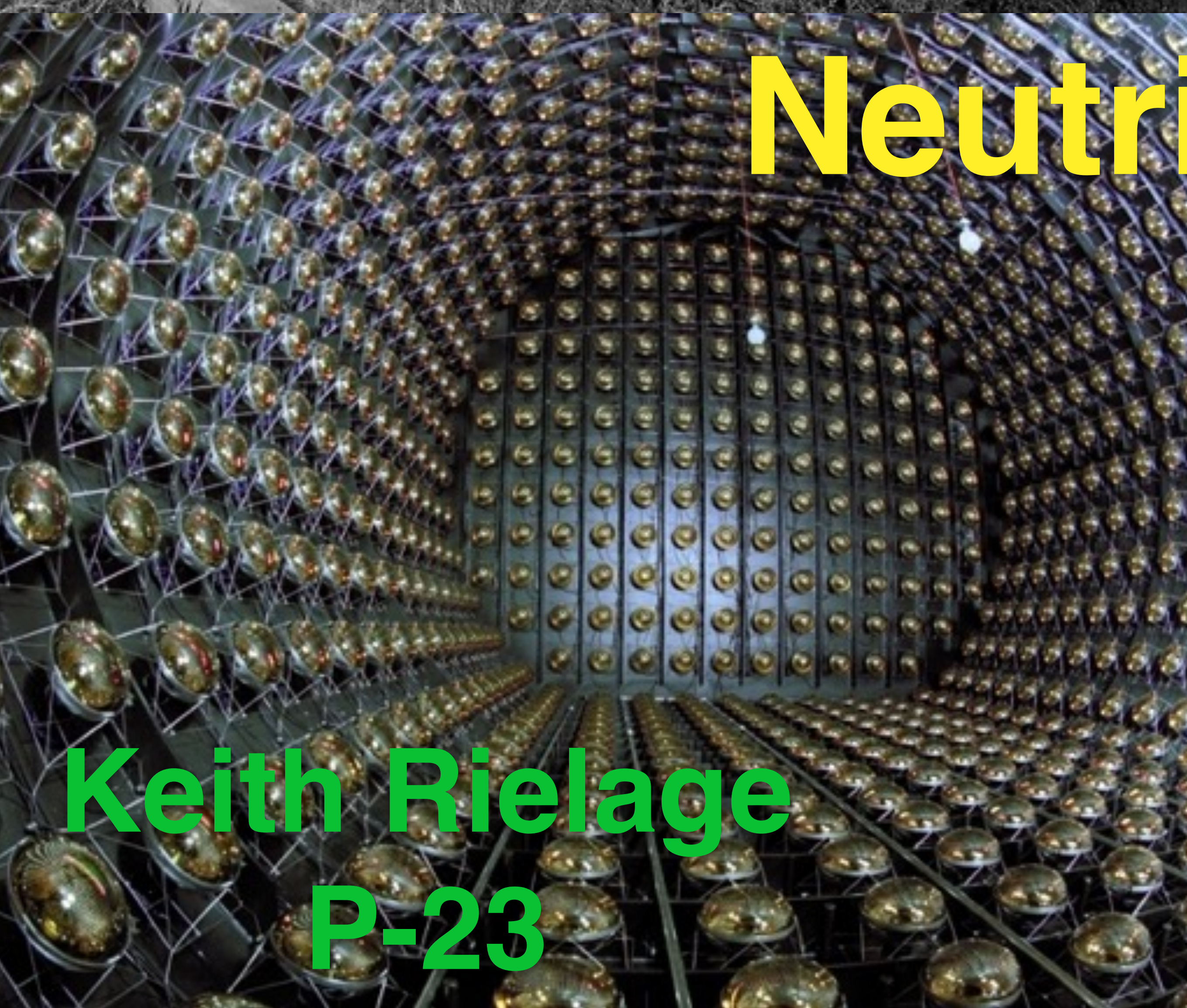
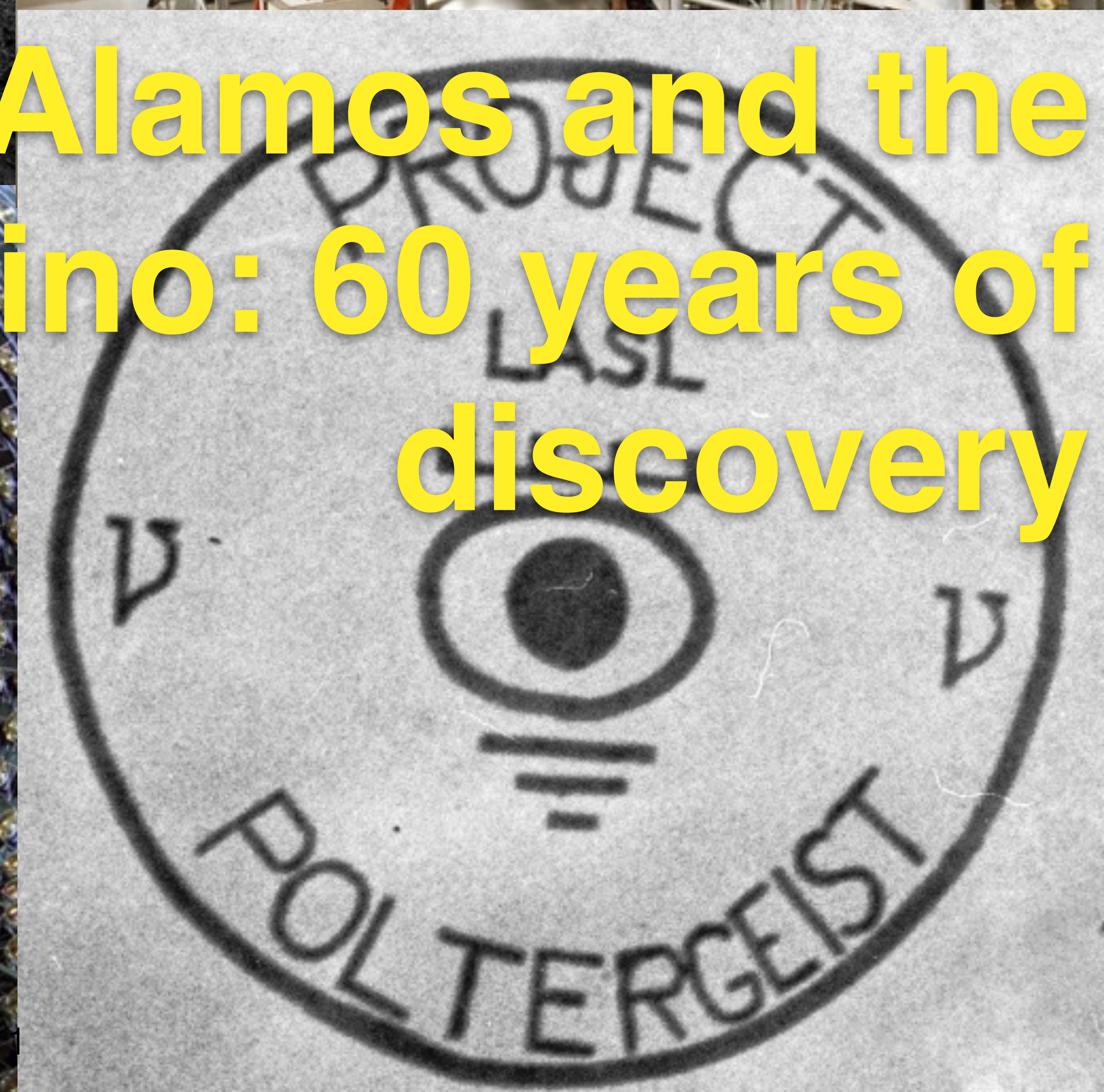
Los Alamos and the Neutrino: 60 years of discovery



Keith Rielage
P-23



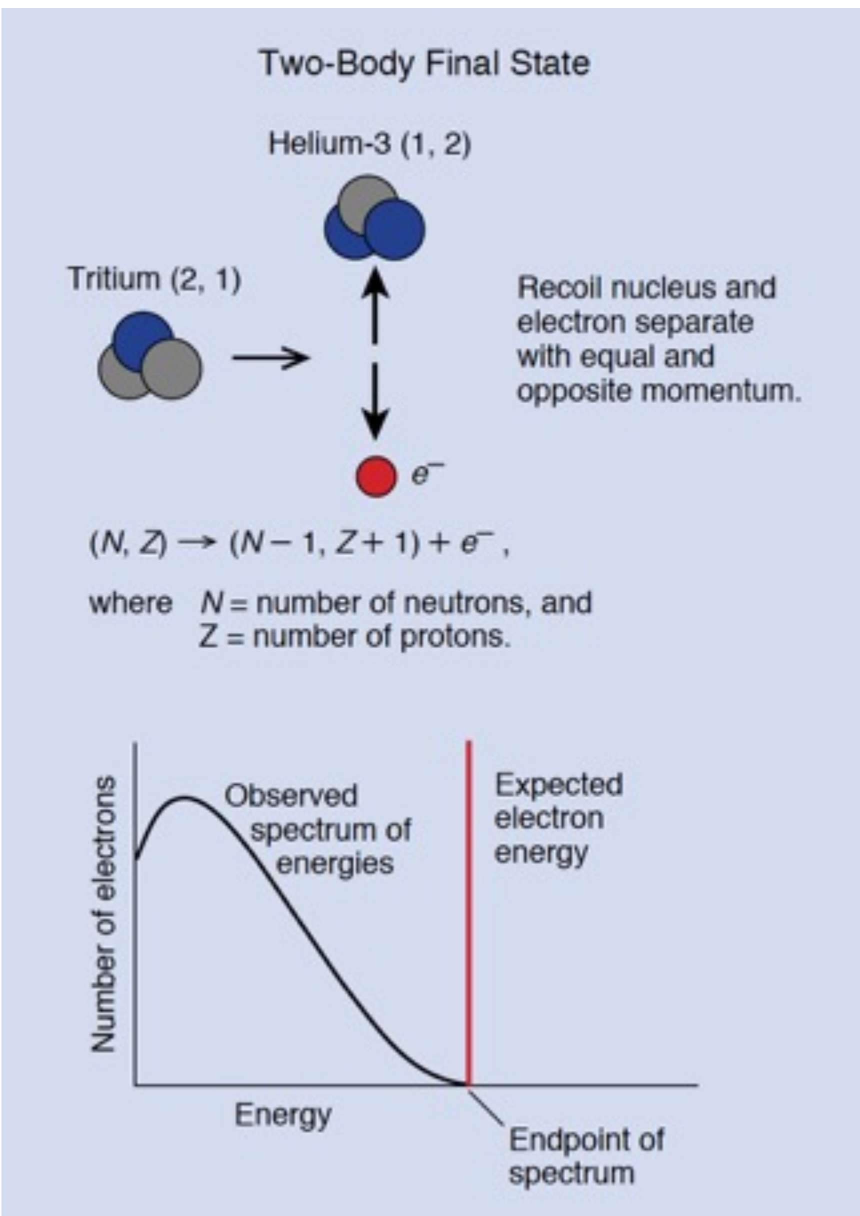
Outline

Historical look:

- Introduction to the neutrino
- First experimental attempts at Los Alamos
- The role of Los Alamos in examining neutrino properties (some examples)
- The future role of Los Alamos in neutrino studies

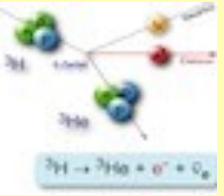
Beta Decay - 1930

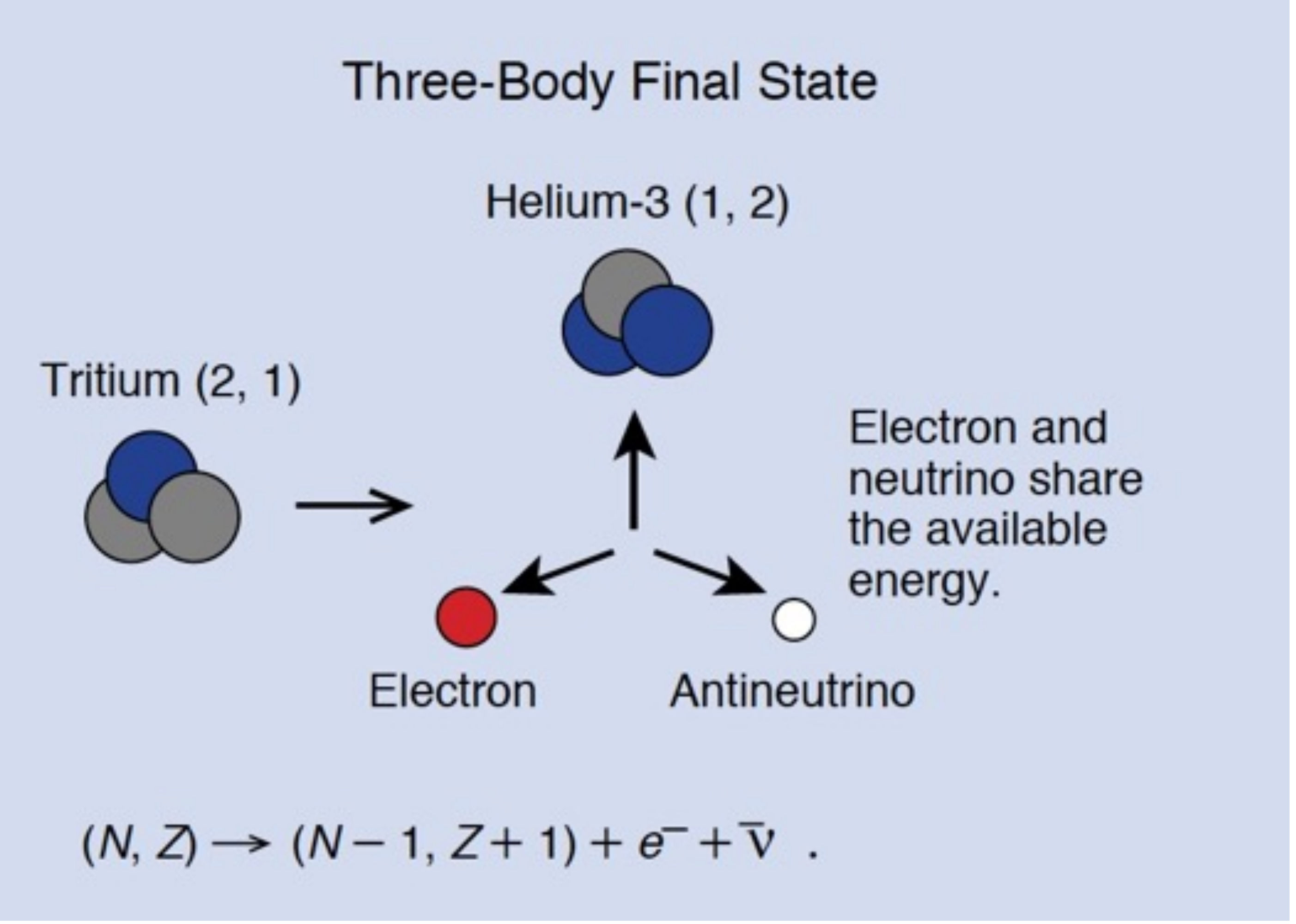
- Early studies of beta decay from 1911 on showed an anomaly
  - A nucleus decays resulting in a change in charge by one unit in the nucleus with a beta (electron or positron) being released



- Result should be an electron or positron with a single value of kinetic energy but a spectrum was observed

Beta Decay - 1930

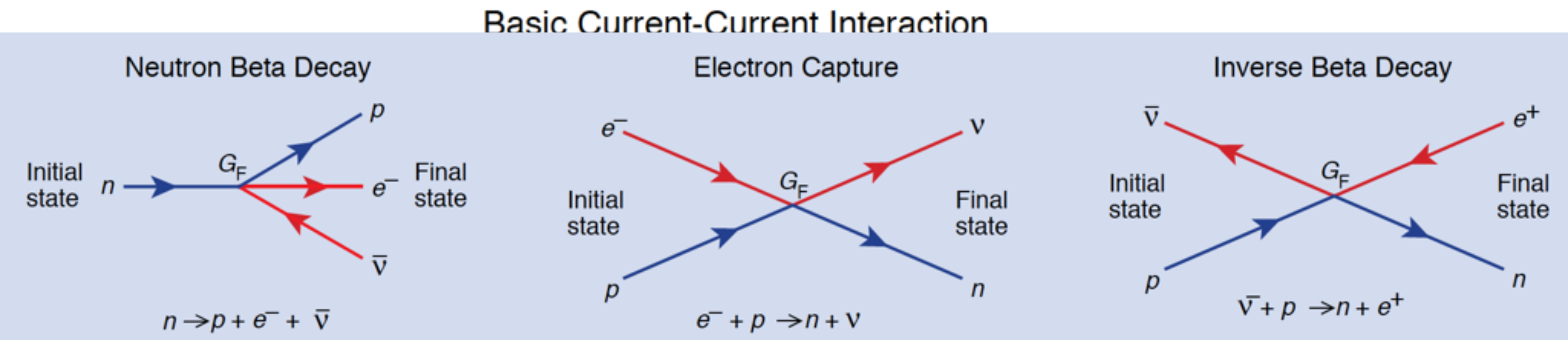




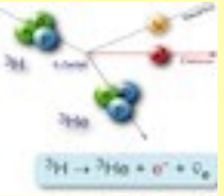
- In 1930, Wolfgang Pauli proposed an additional particle was involved that carried away some of the kinetic energy but was electrically neutral
- He called it the "neutron"
- In 1932, Chadwick discovered the neutron we know today

Fermi's Theory of Beta Decay - 1934

- In 1934, Enrico Fermi developed a more complete theory of beta decay and neutrino processes
- Since the "neutron" was now claimed, he called Pauli's particle the neutrino (little neutral one in Italian)
- Drawing on quantum electrodynamics, Fermi represented beta decay as an interaction of two currents each carrying the weak charge



1934 - 1951



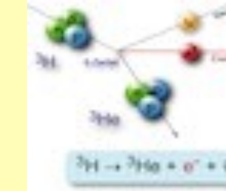
- In 1934, Hans Bethe and Rudolf Peierls calculated the probability that a neutrino would interact
  - The average neutrino would pass through ten light years of water before interacting
  - Concluded "there is no practically possible way of observing the neutrino"

- 1940's the nuclear physics community was a bit busy with other things like fission and fusion and . . .

1945

Trinity test, July 16, 1945

Fred Reines and Los Alamos



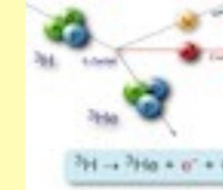
- Fred Reines came to Los Alamos in 1944 to work under Group Leader Richard Feynman (T-4 “Diffusion Problems”) in the Theoretical Division (Hans Bethe, Division Leader)
- At the end of the war he stayed on to study these new devices

Reines, 1956

Fred Reines and Los Alamos

- Became group leader in 1946 of T-1 “Theory of Dragon” Group
  - Dragon was a machine used to “tickle the dragon”, or look at criticality
    - Developed by Otto Frisch
    - Produced short intense bursts of neutrons
- Participated in a number of nuclear tests
  - Operation Crossroads at Bikini Atoll in 1946
  - Operation Sandstone at Eniwetok Atoll in 1948
  - Operation Ranger and Operation Buster-Jangle at Nevada Test Site
- Was the Director of Operation Greenhouse in 1951

Fred Reines and Los Alamos



- Reines experienced the "can do" attitude of Los Alamos during the George Shot (part of Operation Greenhouse)

- To shield the signal cables from the gamma flux during the explosion, the only thing available for shielding of the magnitude needed was the island itself. So half the island was dug up and dumped on top of the cables

Only at Los Alamos

• In 1951, Reines asked for a "leave in residence" from weapons work to think about other physics. J Carson Mark, Theoretical Division Leader granted it.

• He turned to an idea to detect the elusive neutrino by using an intense (but brief) source of neutrinos — the bomb

• Being at Los Alamos, he was able to discuss the idea with Enrico Fermi and Hans Bethe at length and both agreed it was the most promising source

Only at Los Alamos

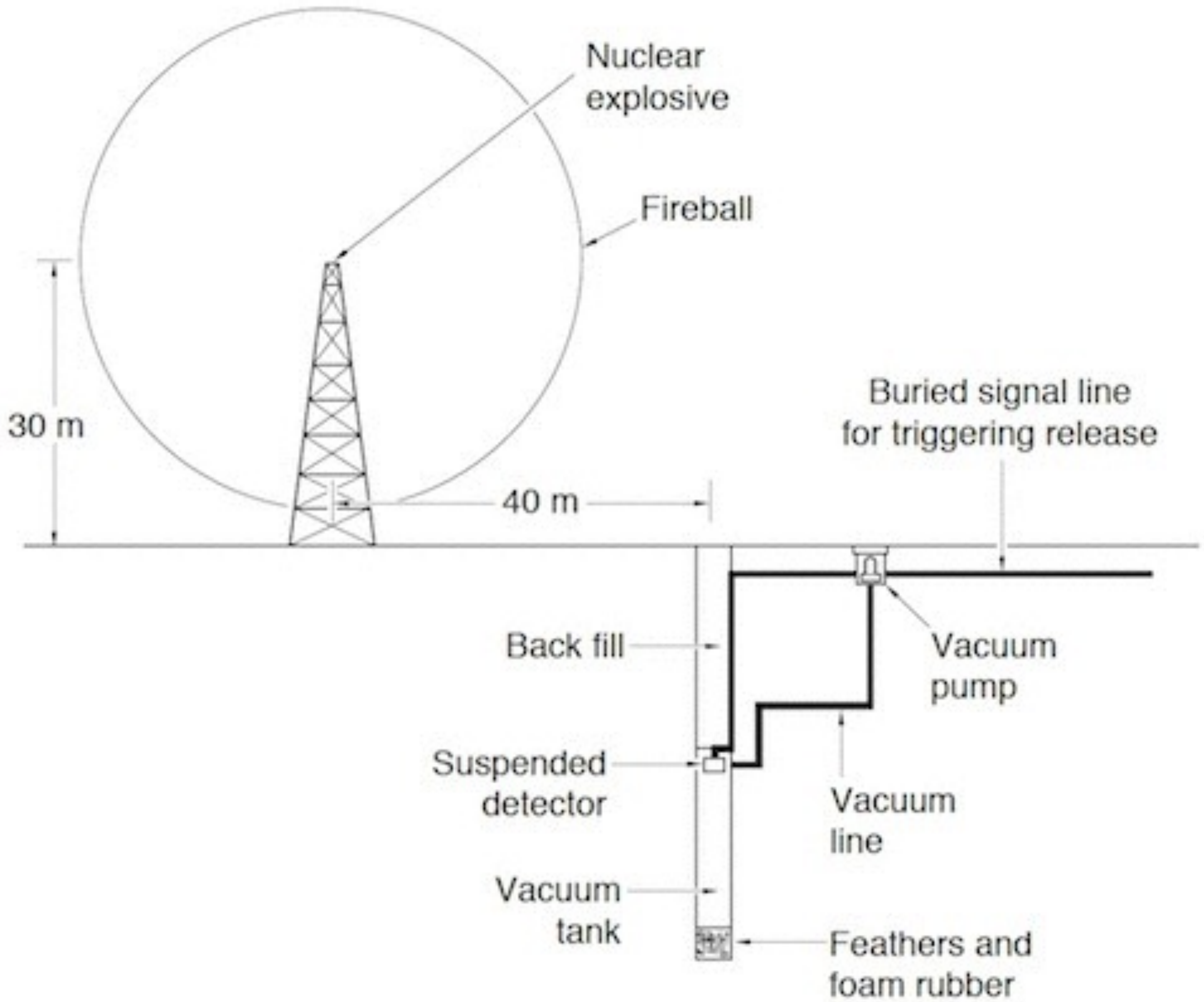
- A new detector was available: the liquid scintillator
  - Liquid doped with the proper chemical cocktail that produces light when energy is deposited as a particle interacts in the liquid
- The light produced could be read out using the relatively new photomultiplier tube
- Los Alamos had experts in liquid scintillator and the health physics group (which was developing tools to monitor radiation and its effects) had several that were "large" (a liter in volume)

Only at Los Alamos

- Why did Reines decide to pursue the detection of the neutrino?
  - “Because everyone said, you couldn’t do it”
- After meeting with Fermi, he was stumped on how to build the necessary detector
- But on a plane trip to Princeton, he was grounded in Kansas City and began to talk with Clyde Cowan, a chemical engineer

Cowan, 1950’s

First Idea



Nuclear explosive
Fireball
30 m
40 m
Buried signal line for triggering release
Back fill
Vacuum pump
Suspended detector
Vacuum line
Vacuum tank
Feathers and foam rubber

First Idea

- Simple idea:
  - use photomultiplier tubes to view a pot of liquid scintillator about a cubic meter in volume
  - drop this detector in a shaft next to a nuclear test (so that the earth shaking would not destroy the detector)
  - look for the inverse beta decay reaction
    - antineutrino + proton → neutron + positron
    - signal would be a few counts during the blast
    - able to set a limit of roughly 10^{-39} cm^2/proton — about 1000x more sensitive than the best limits but 4 orders of magnitude less than Bethe and Peierls predicted
- They approached Norris Bradbury, the Director, who approved the idea
  - Construction on a shaft began in Nevada, design started on vacuum tank

Better Idea

Cowan, Reines, and ?, 1954

- In October 1952, made two realizations:
  - Could reduce the backgrounds by looking for the delayed coincidence between the positron and the neutron if it captured on something (like boron or cadmium loaded into the detector)
  - Could use the Hanford pile reactor as a source of neutrinos
- Herr Auge was built with 90 photomultiplier tubes
- Project Poltergeist was ready

Side Benefit

Wright Langham (H-4) being lowered, 1953

- Soon learned that this type of detector was almost 100% efficient at detecting gammas and neutrons
- The detector was about the size of a person
- In early 1953, made a detector with a well in the center to count the amount of ^{40}K in humans
- Direct spin-off, 1956, the whole-body counter

Hanford Tests - 1953

- Placed Herr Auge about six feet from the Hanford pile
- Shielding was parafin wax and borax blocks and lead to stop neutrons
- Tried a number of scintillator cocktail mixtures: toluene, mineral oil, terphenyl
- Cadmium was used for neutron capture

Herr Auge & Shielding, 1954

Hanford Tests - 1953

• Expected a coincidence signal rate of 0.1 - 0.3 counts per minute between positron like signals and neutron capture like signals within 9 μs

• After trying numerous scintillator cocktails and changes in shielding configurations found a fairly consistent 5 counts per minute with reactor on and slightly less when reactor was off

• Suspected that neutrons created by cosmic rays interacting in their shielding were the cause

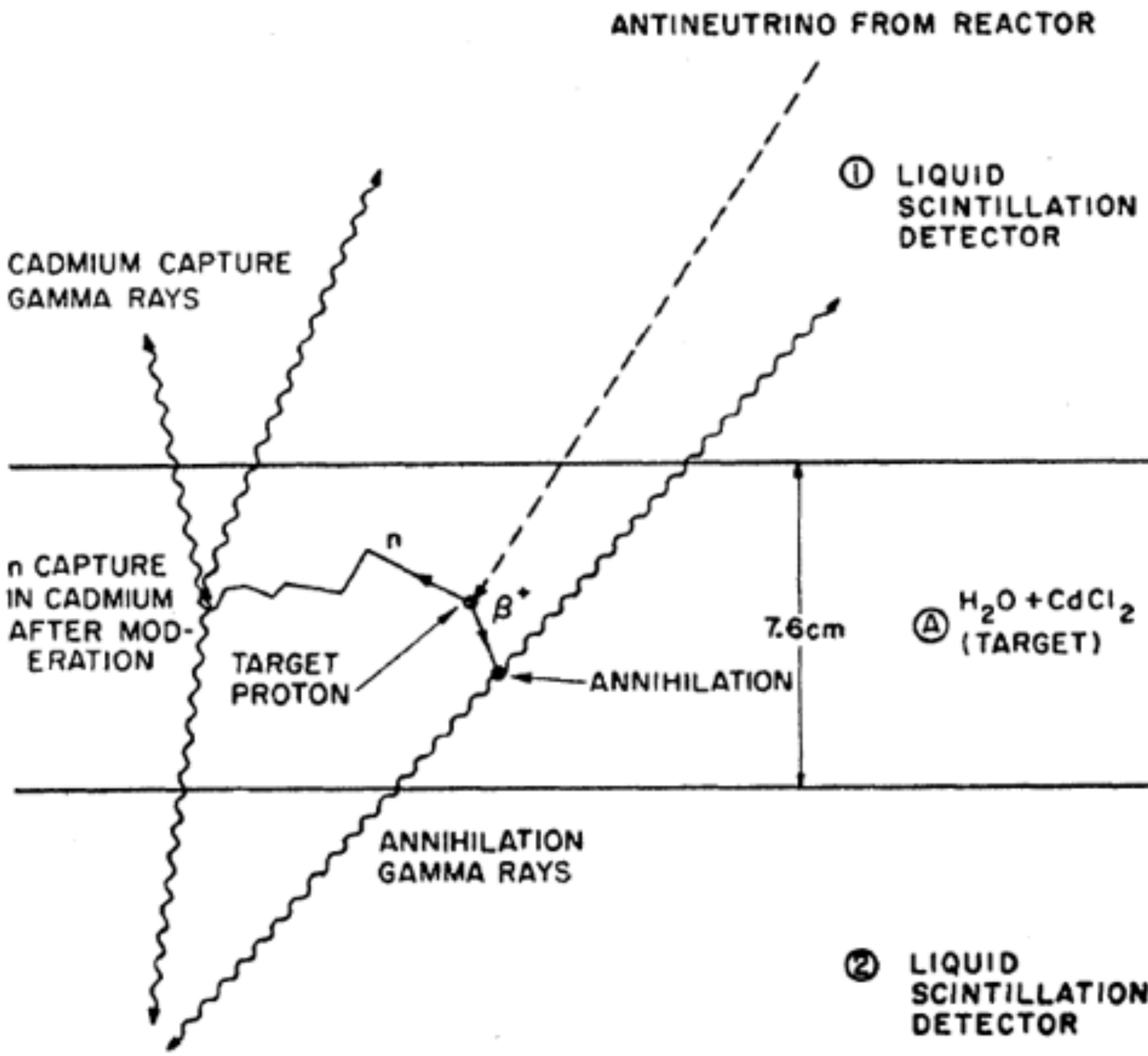
Hanford Tests - 1953

Hanford Team (L-R): F. Newton Hayes, Capt. W.A. Walker, T.J. White, Fred Reines, E.C. Anderson, Clyde Cowan

Los Alamos Tests

- Later in 1953, they tested a detector at Los Alamos and in the tunnel at TA-41 and saw a reduced rate compared to the surface

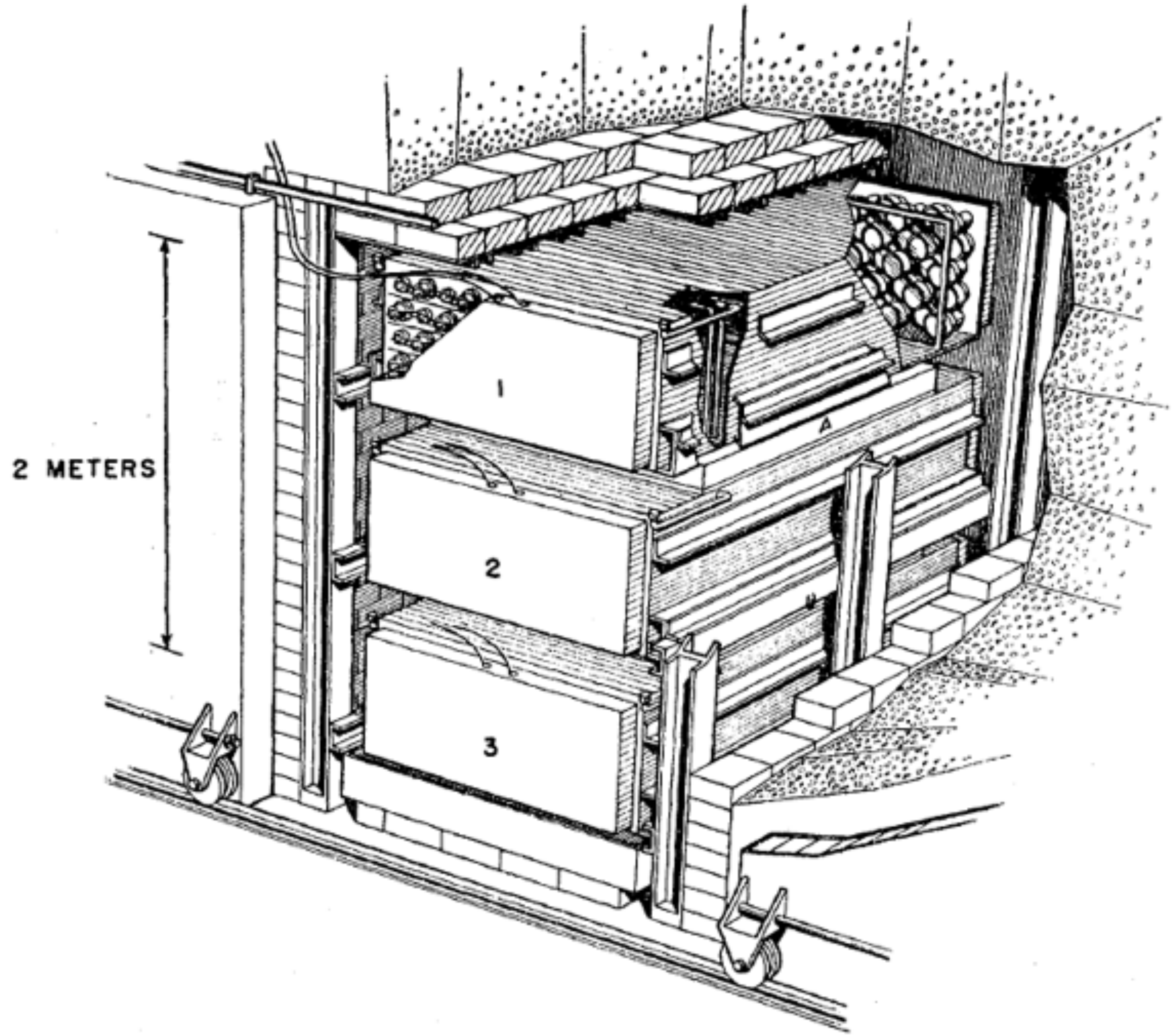
Even Better Idea



- What if you could separate the neutron capture event from the positron signal more cleanly by using a target and several liquid scintillator volumes?

Savannah River Tests - 1955

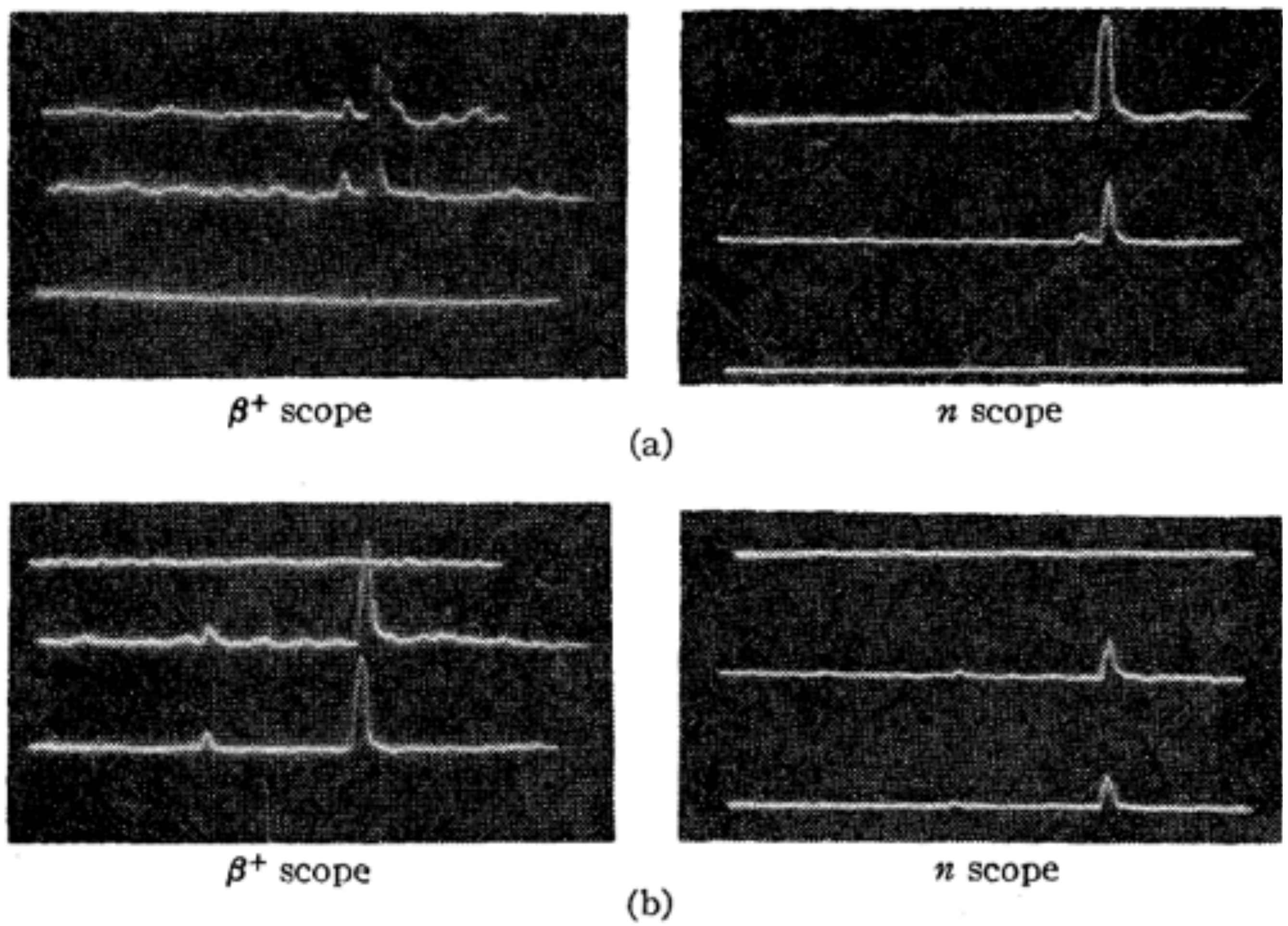
Reines and Cowan, 1956

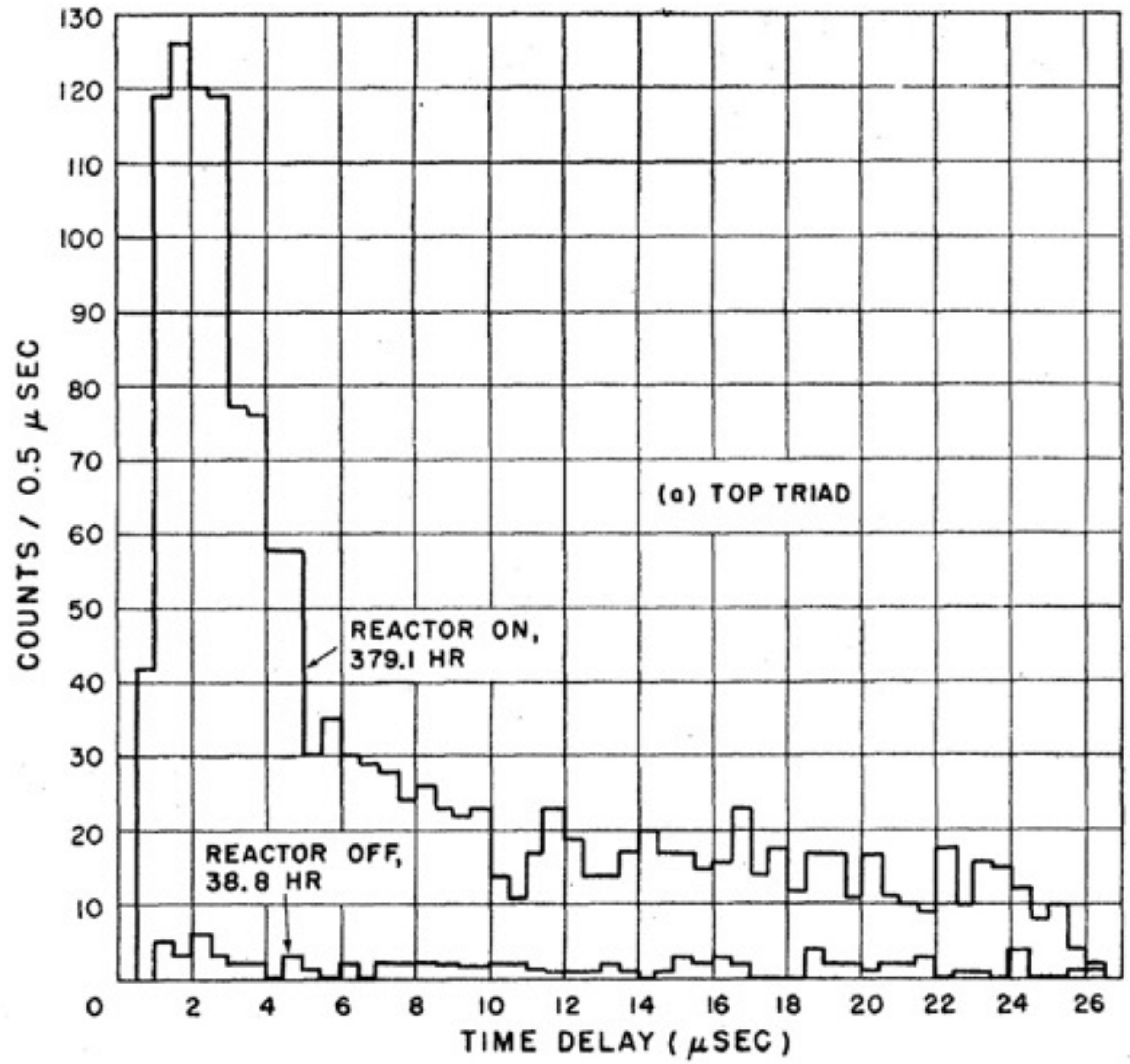


Savannah River Tests - 1955

- In November 1955, moved the detector to the new Savannah River Plant in SC — more powerful reactor, 11 meters of concrete to reactor, 12 meters of overburden to shield from cosmic rays
- Over five months took 900 hours of data with reactor on, 250 hours with reactor off
- Performed extensive calibrations:
  - ^{64}Co dissolved in target to produce positrons
  - Doubled amount of Cd to see if number of captures increased
  - Reduced the number of protons in the target by mixing in heavy water
  - Used the data from 11 to 30 μs to estimate accidentals

Savannah River Tests - 1955-6

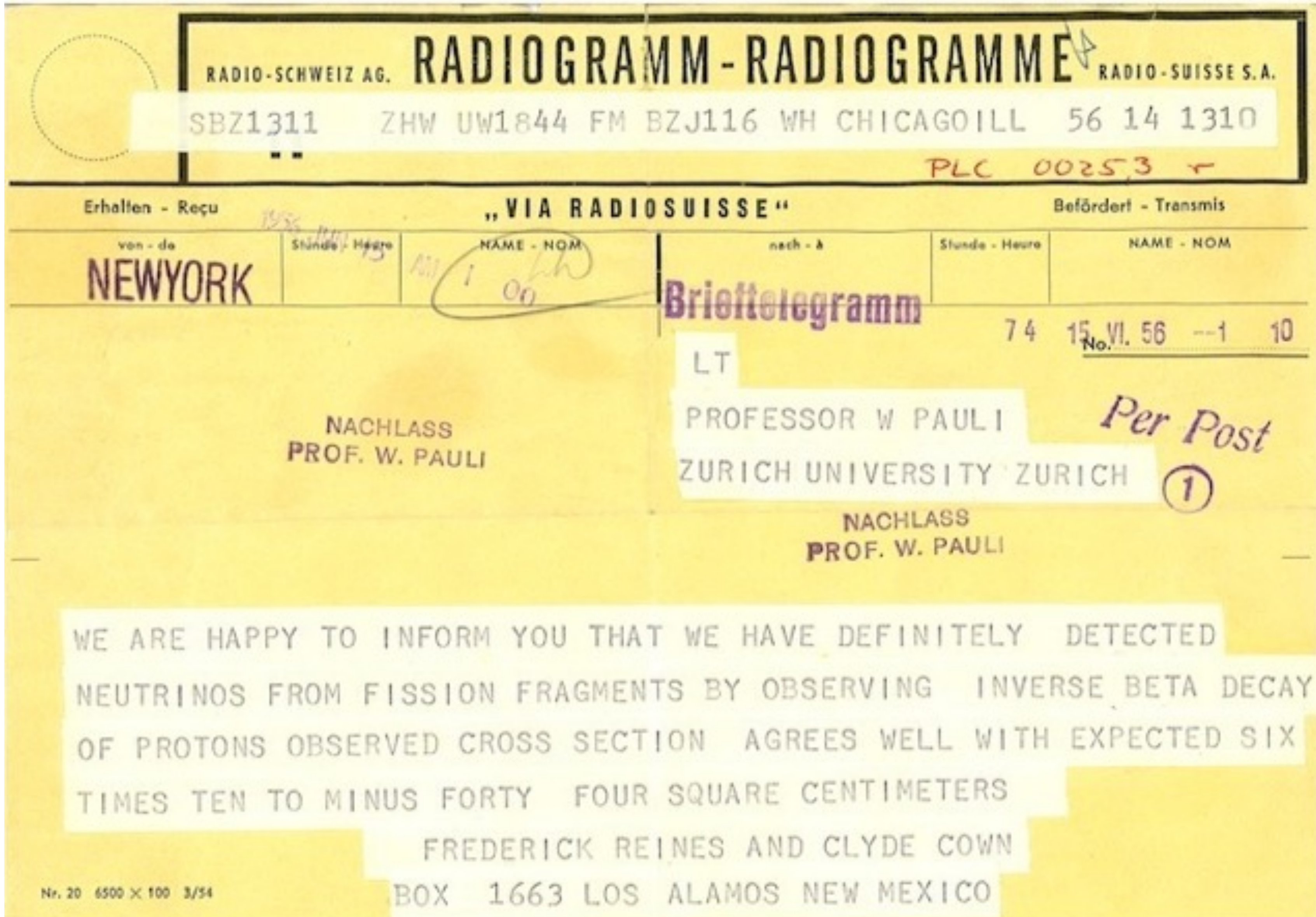




Savannah River Tests - 1955-6

Savannah Team: (Back L-R) Clyde Cowan, F.B. Harrison, Austin McGuire, Fred Reines, Martin Warren, (Front L-R) Richard Jones, Forrest Rice, Herald Kruse

Discovery!



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 X 100 3/54

- June 14, 1956 - Reines and Cowan sent a telegram to Pauli announcing the detection
- Pauli was at CERN and read it to those attending the meeting

Discovery!

Friedrich REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

erh. 15.6.56 / 15.30 h
als Night letter

- Pauli sent a response that never made it
- A brief Science article appeared in July 1956 and in 1960 a full paper was published in Physical Review

Nobel Prize - 1995

- In October 1995, Fred Reines won the Nobel Prize
- Clyde Cowan had passed away in 1974

- Three other Nobel Prizes for neutrinos:
  - 1988 - discovery of the muon neutrino
  - 2002 - detection of solar and supernova neutrinos
  - 2015 - discovery of neutrino oscillations

Neutrino Work Continues

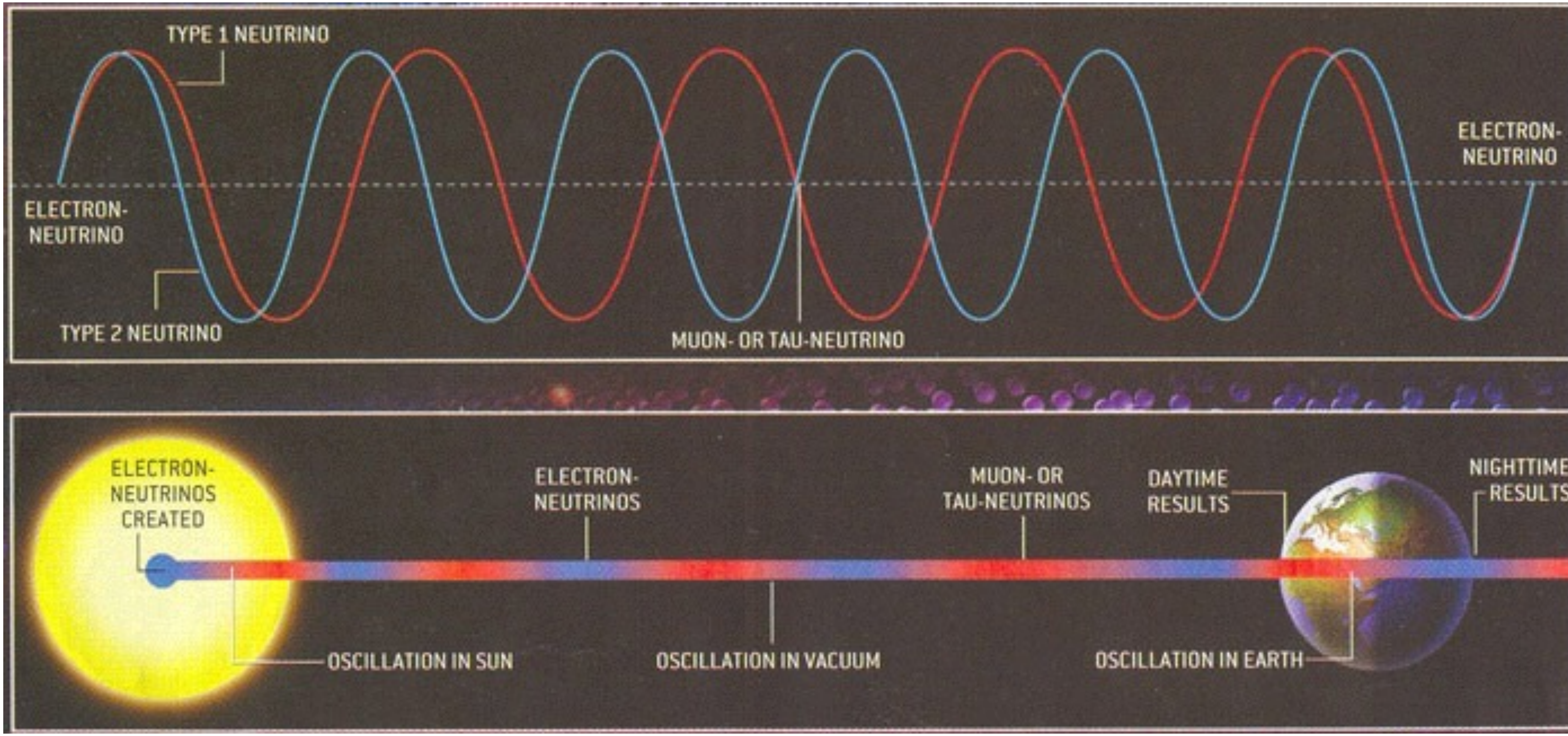
- Cowan left the lab in 1957 for George Washington University, then Catholic University of America in 1959
- Reines left the lab in 1959, first to Case Western, then to University of California Irvine in 1966
- But neutrino research continued with a growing group of people at the lab and around the world

Other Neutrino Properties

- 1942 - Sakata and Inoue propose the pi-mu scheme with a neutrino to accompany the muon
- 1962 - muon neutrino discovered by Lederman, Schwartz, and Steinberger at Brookhaven
- 1965 - first natural neutrinos detected by Reines and colleagues in South African gold mine, and by Menon and colleagues in gold fields in India
- 1977 - tau lepton discovered by Martin Perl and colleagues, accompanied by tau neutrino

- So now we have 3 neutrinos

Neutrino Oscillations

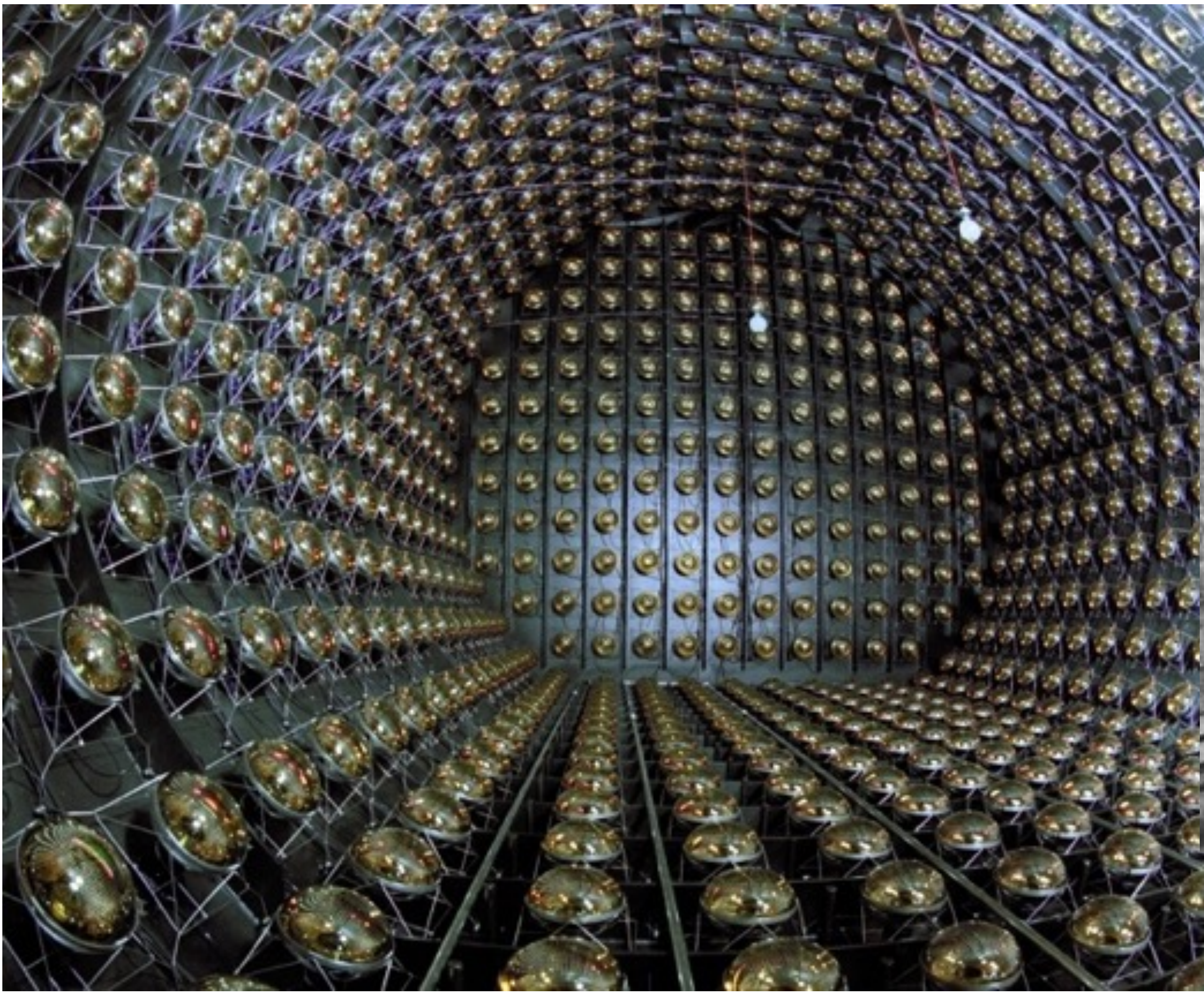


- 1962: Maki, Nakagawa and Sakata introduce neutrino flavor mixing and flavor oscillations.
- 1978/1986: Wolfenstein, Mikheyev, and Smirnov propose neutrinos oscillate in matter.

LAMPF - 1972-1995

Experiment	Years	Reactions Observed	Principal Scientific Goals
E-31	1975–1980	$\bar{\nu}_e + p \rightarrow e^+ + n$ $\nu_e + \mathrm{D} \rightarrow e^- + p + p$	Deduce the form of the muon-family-number conservation law
E-225	1975–1993	$\nu_e + e^- \rightarrow e^- + \nu_e$ $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + \mathrm{X}$	Measure the scattering cross section between electrons and electron neutrinos Measure the electron neutrino cross section on ^{12}C (X is another atom, typically ^{12}N)
E-645	1980–1993	$\bar{\nu}_e + p \rightarrow e^+ + n$	Search for $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations
E-764	1982–1992	$\nu_e + {}^{12}\mathrm{C} \rightarrow \mu^- + \mathrm{X}$ $\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + \mathrm{X}$	Search for $\nu_\mu \leftrightarrow \nu_e$ oscillations Measure the muon neutrino cross section on ^{12}C
E-1173	1989–1998	$\bar{\nu}_e + p \rightarrow e^+ + n$ $\nu_e + {}^{12}\mathrm{C} \rightarrow \mu^- + \mathrm{X}$	Search for $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations Search for $\nu_\mu \leftrightarrow \nu_e$ oscillations

LSND - E1173



LSND Collaboration, circa 1990

- Series of experiments started to look for oscillations
- Made use of a large cosmic-ray veto shield
- Construction started in 1989 on E1173 - called the Liquid Scintillator Neutrino Detector (LSND)

LSND - E1173

- LSND took Herr Auge to the extreme:
  - 52,000 gallons of mineral oil and b-PBD with 1000 photomultiplier tubes
  - Inside a cosmic-ray veto shield
- Looking for electron neutrinos that oscillate from muon neutrinos
- Proton beam hit water, producing pions, stopped in copper and decayed into muons and muon neutrinos

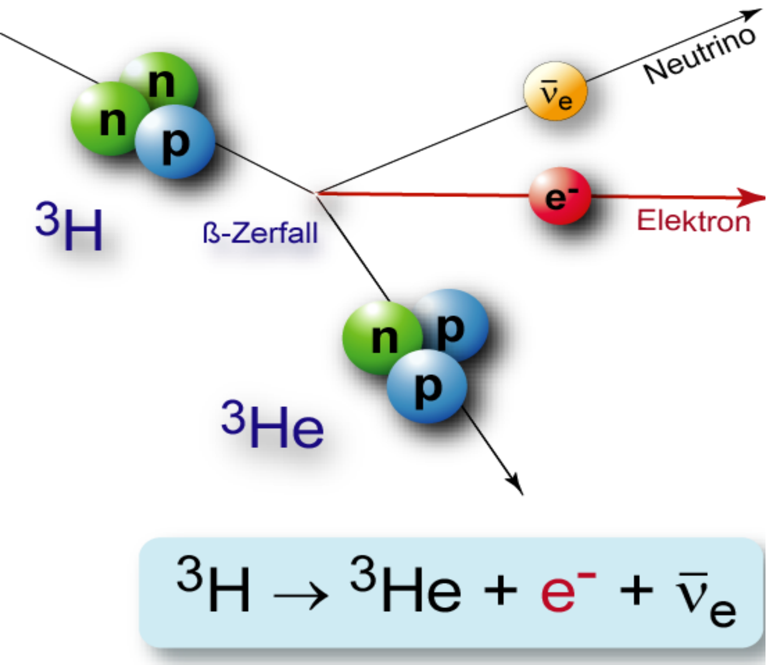
Table 1.4. Numbers of LSND beam-on events that satisfy the selection criteria for the primary $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search with $R_\gamma > 1$, $R_\gamma > 10$, and $R_\gamma > 100$. Also shown are the beam-off background, the estimated neutrino background, and the excess of events that is consistent with neutrino oscillations.

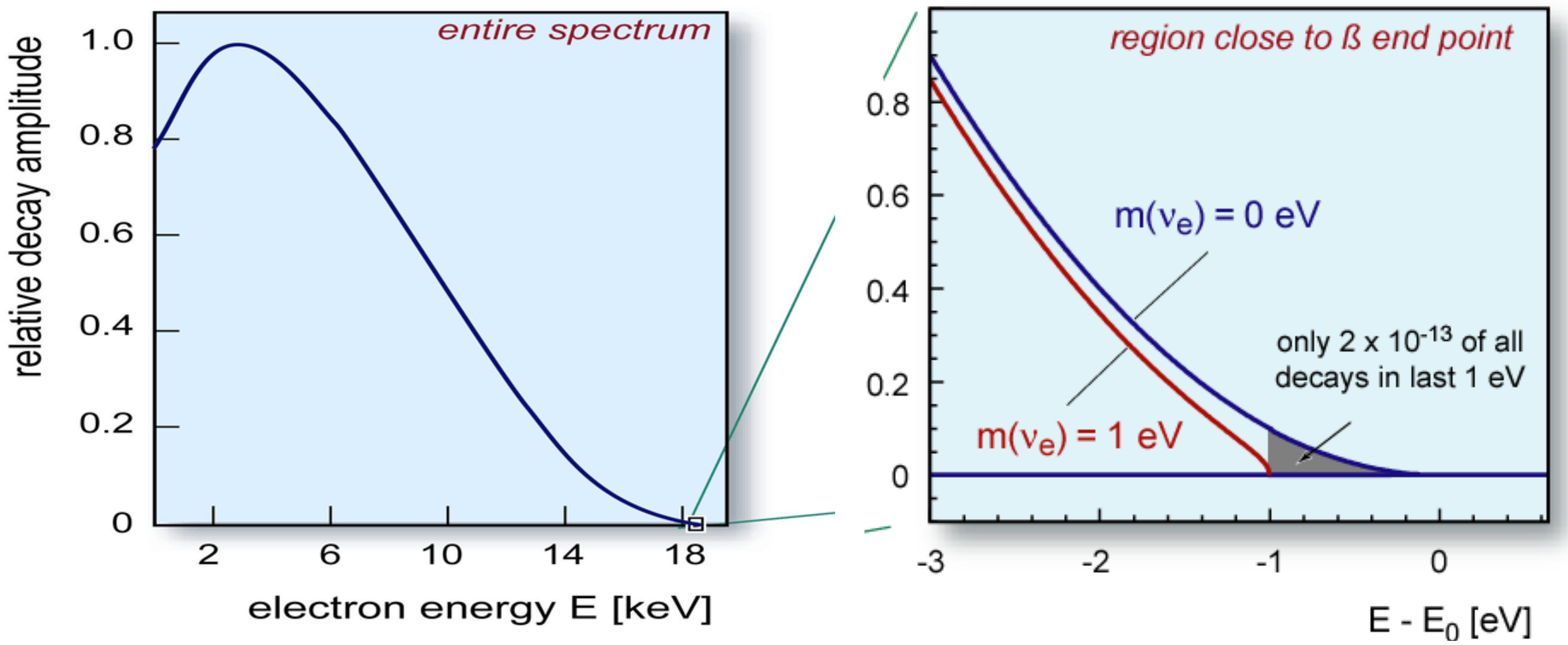
Selection	Beam-On Events	Beam-Off Background	ν Background	Event Excess
$R_\gamma > 1$	205	106.8 ± 2.5	39.2 ± 3.1	$59.0 \pm 14.5 \pm 3.1$
$R_\gamma > 10$	86	36.9 ± 1.5	16.9 ± 2.3	$32.2 \pm 9.4 \pm 2.3$
$R_\gamma > 100$	27	8.3 ± 0.7	5.4 ± 1.0	$13.3 \pm 5.2 \pm 1.0$

LSND - E1173

- LSND took Herr Auge to the extreme:
  - 52,000 gallons of mineral oil and b-PBD with 1000 photomultiplier tubes
  - Inside a cosmic-ray veto shield
- Looking for electron neutrinos that oscillate from muon neutrinos
- Proton beam hit water, producing pions, stopped in copper and decayed into muons and muon neutrinos
- Experiment used muon neutrinos and muon antineutrinos
- Observed excess of events at 3.8σ of electron antineutrinos consistent with oscillations showing a $\Delta m^2 \sim 1$ eV^2 - could be a fourth type of neutrino - sterile

Beta Decay Experiments

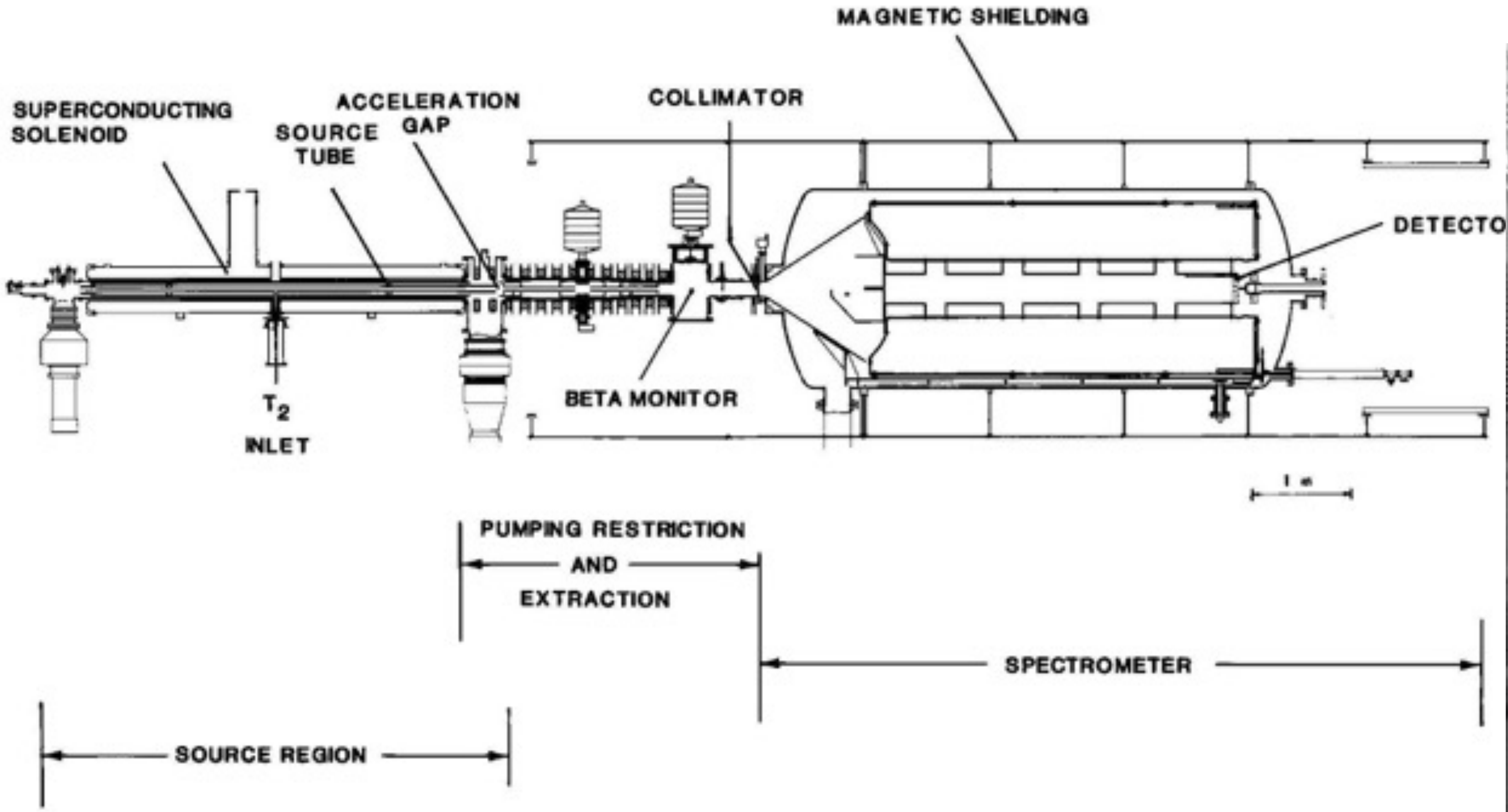


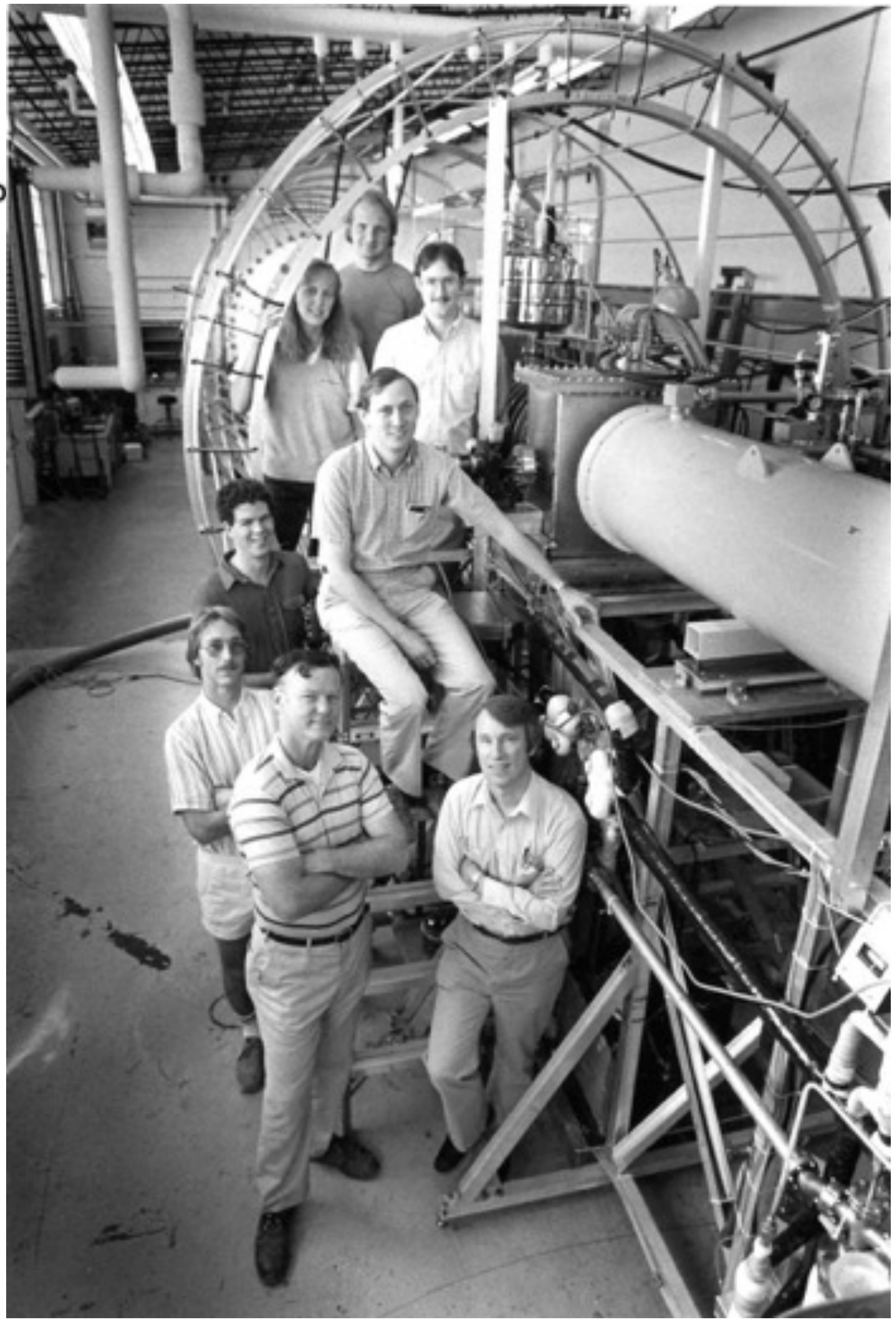


Looking for endpoint distortion to determine the mass of the neutrino

Los Alamos was first to use gaseous tritium

Beta Decay - 1987





- In 1985, beta decay measurements suggested a mass of 17 keV
- Renewed interest in using beta decay
- Los Alamos was the first to use a gaseous tritium source and set the best limits for a decade

Herb Chen

- In the 1970's Herb Chen led the E-225 experiment at LAMPF to measure the charged-current scattering of electron neutrinos from electrons and its cross section
- This work would lead him to think about a way to solve the "solar neutrino problem"

Solar Neutrino Production

SSM Energy Generation

$p + p \rightarrow {}^2H + e^+ + \nu_e$ $\quad$ $p + e^- + p \rightarrow {}^2H + \nu_e$

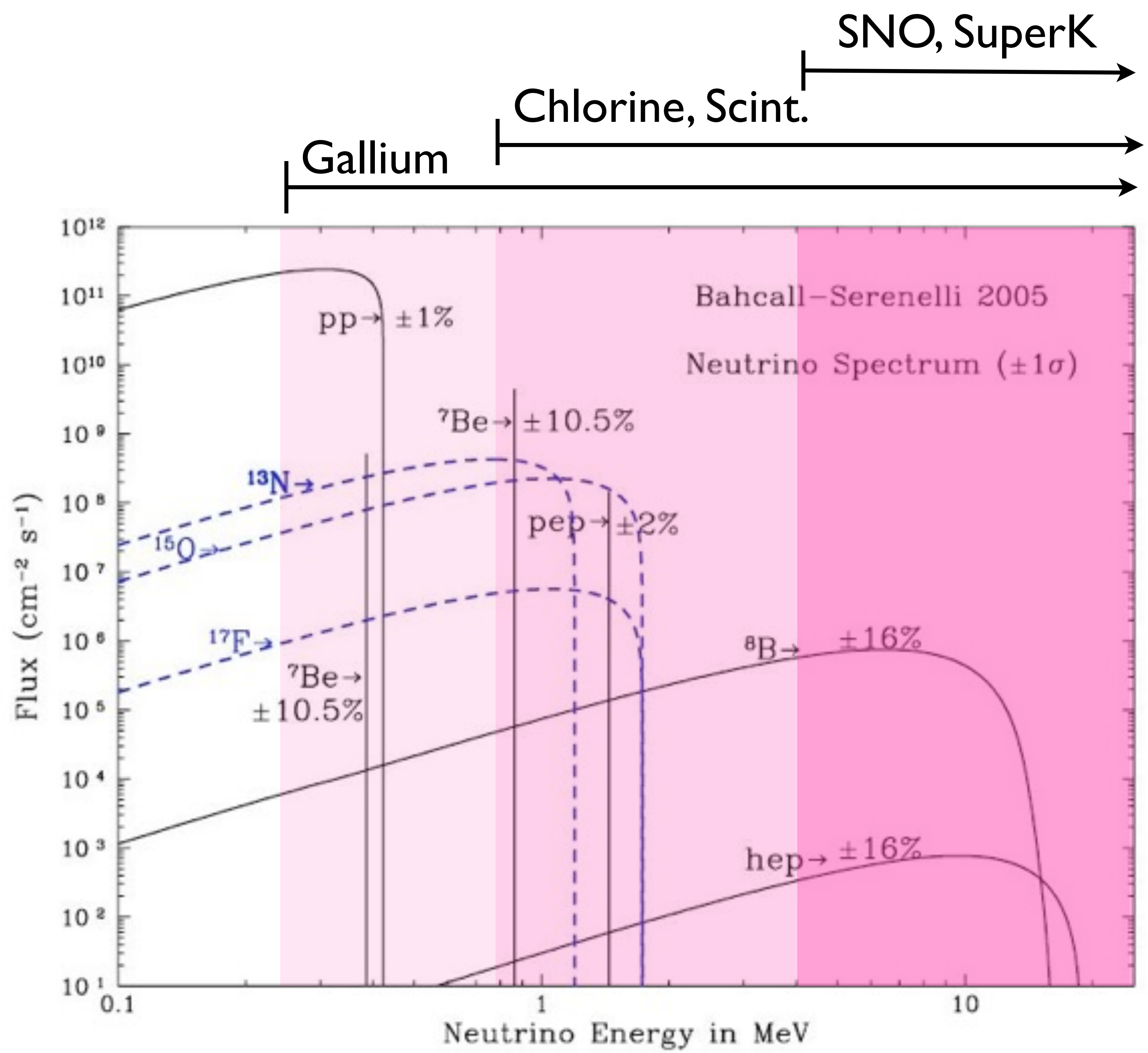
$^2H + p \rightarrow {}^3He + \gamma$

$^3He + {}^3He \rightarrow {}^4He + 2p$ $\quad$ $^3He + p \rightarrow \alpha + e^+ + \nu_e$

$^3He + \alpha \rightarrow {}^7Be + \gamma$

$^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ $\quad$ $^7Be + p \rightarrow {}^8B + \gamma$

$^7Li + p \rightarrow \alpha + \alpha$ $\quad$ $^8B \rightarrow 2\,\alpha + e^+ + \nu_e$



The Beginning: The Solar Neutrino Problem

1967: Ray Davis detects solar neutrinos, flux is less than predicted by John Bahcall's model

1970's-1980's: Experiments utilizing chlorine, gallium, water continue to report flux below the Standard Solar Model

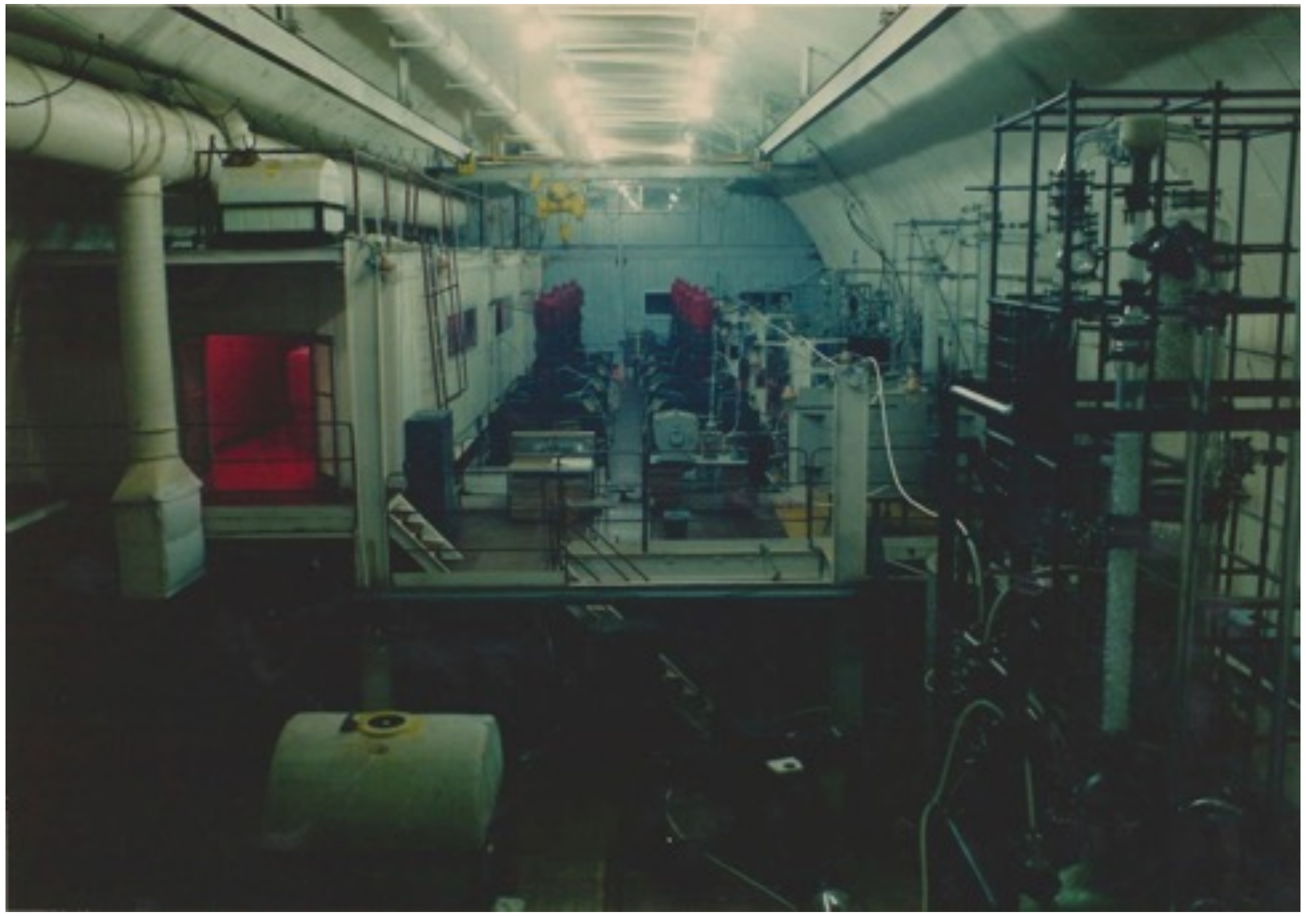
Where did the solar neutrinos go?

Do they oscillate between mass eigenstates as they travel through vacuum and pass through matter?

1984: Herb Chen proposes the use of heavy water in a solar neutrino detector to check for all active 'flavors'

The Sudbury Neutrino Observatory (SNO) is born!

Solar Neutrino Problem



- Even brought unlikely partners together: Soviet-American Gallium Experiment (SAGE) involved Los Alamos, Institute for Nuclear Research (Moscow), Joint Institute for Nuclear Research (Dubna)
- Used 50 tonnes of gallium located in Caucasus Mountains to measure solar neutrino rate

Why is SNO unique?

Key physics signatures

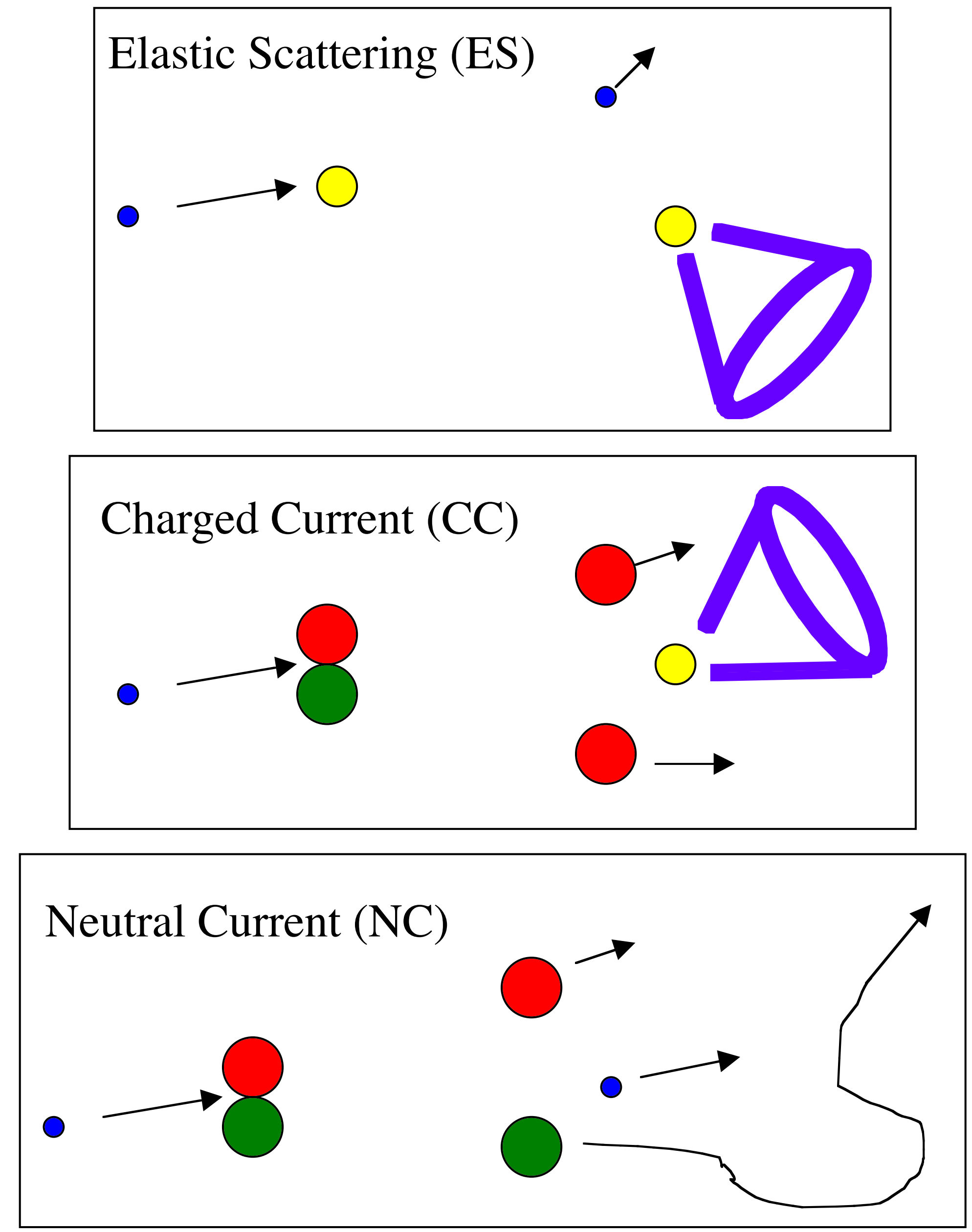
Neutrino interactions in heavy water:

- Elastic Scattering: $\nu_x + e^- \to e^- + \nu_x$
  - Mostly sensitive to ν_e
  - Strong directional sensitivity
- Charged Current: $d + \nu_e \to p + p + e^-$
  - Sensitive to ν_e only
  - Can measure ν_e energy spectrum
- Neutral Current: $d + \nu_x \to p + n + \nu_x$
  - Equally sensitive to all three flavors
  - SNO measures liberated neutron three ways
- CC/NC ratio < 1 → definitive evidence of neutrino flavor change

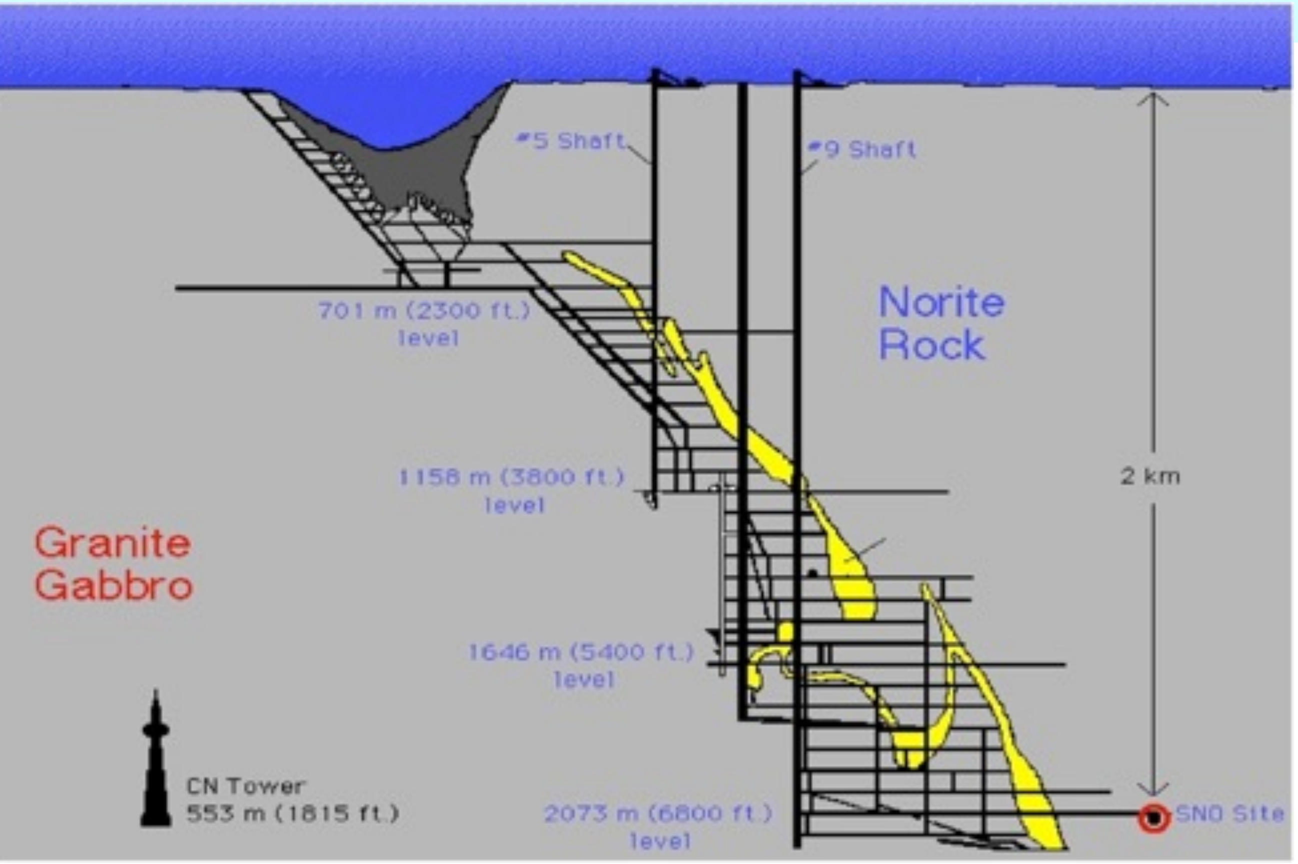
$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

$$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}$$

Φ_{day} vs Φ_{night}



Sudbury Neutrino Observatory



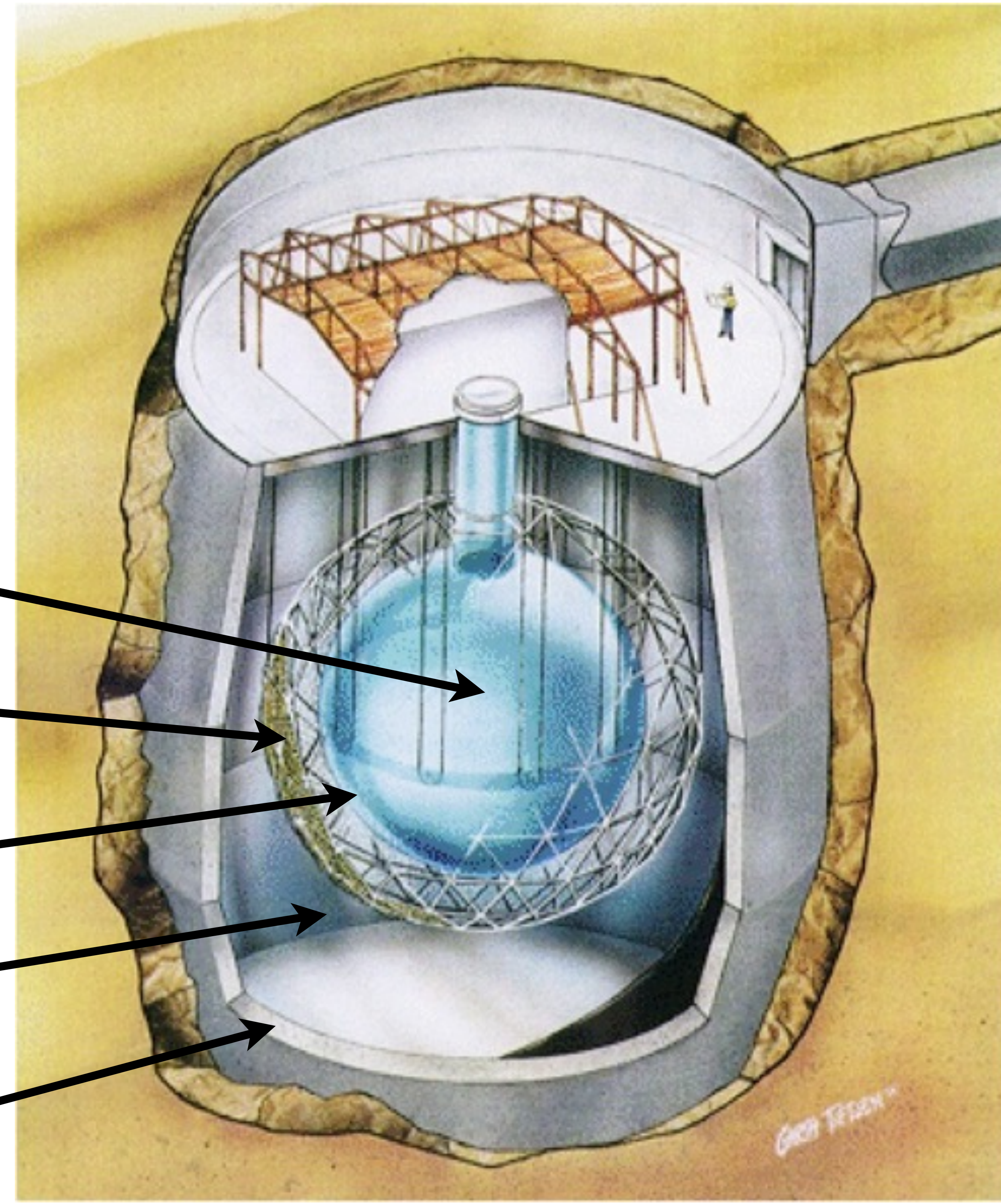
1000 tonnes D_2O

Support structure for 9500 PMTS, 54% coverage

12 m diameter Acrylic Vessel

7000 tonnes H_2O shielding

Urylon liner and Radon seal

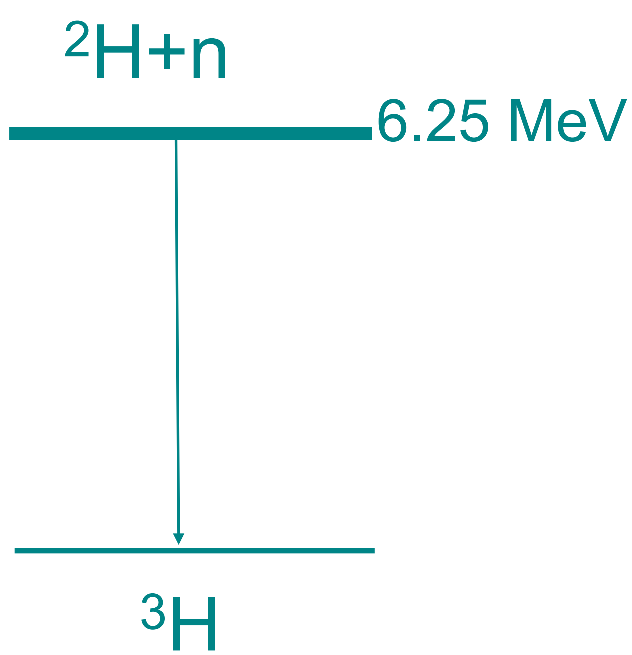


SNO - Three Neutron Detection Methods

Phase I (D_2O)

Nov. 99 - May 01

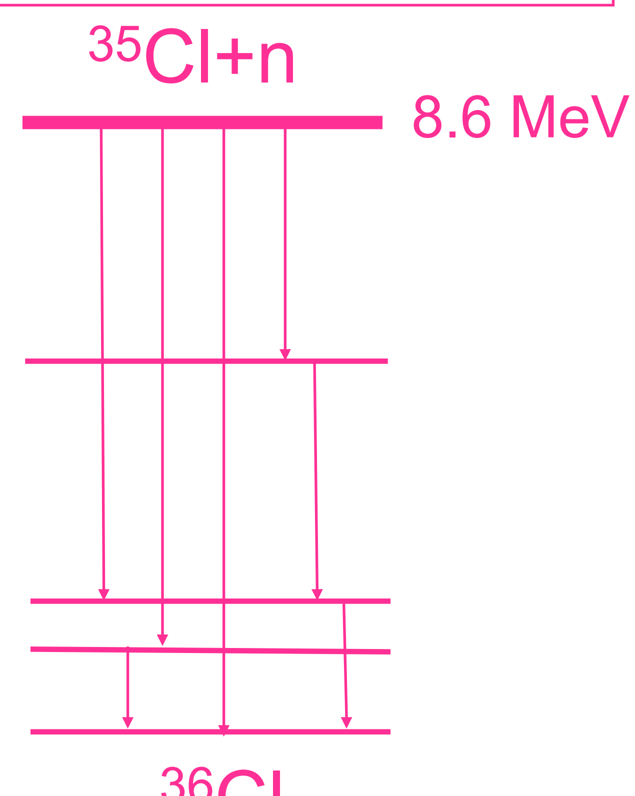
n captures on
$^{2}H(n, \gamma)^{3}H$
σ = 0.0005 b
Observe 6.25 MeV γ
PMT array readout
Good CC



Phase II (salt)

July 01 - Sep. 03

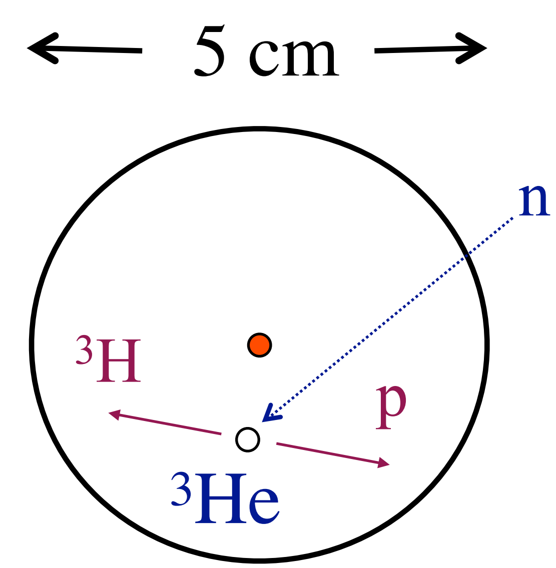
2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
σ = 44 b
Observe multiple γ's
PMT array readout
Enhanced NC



Phase III (^{3}He)

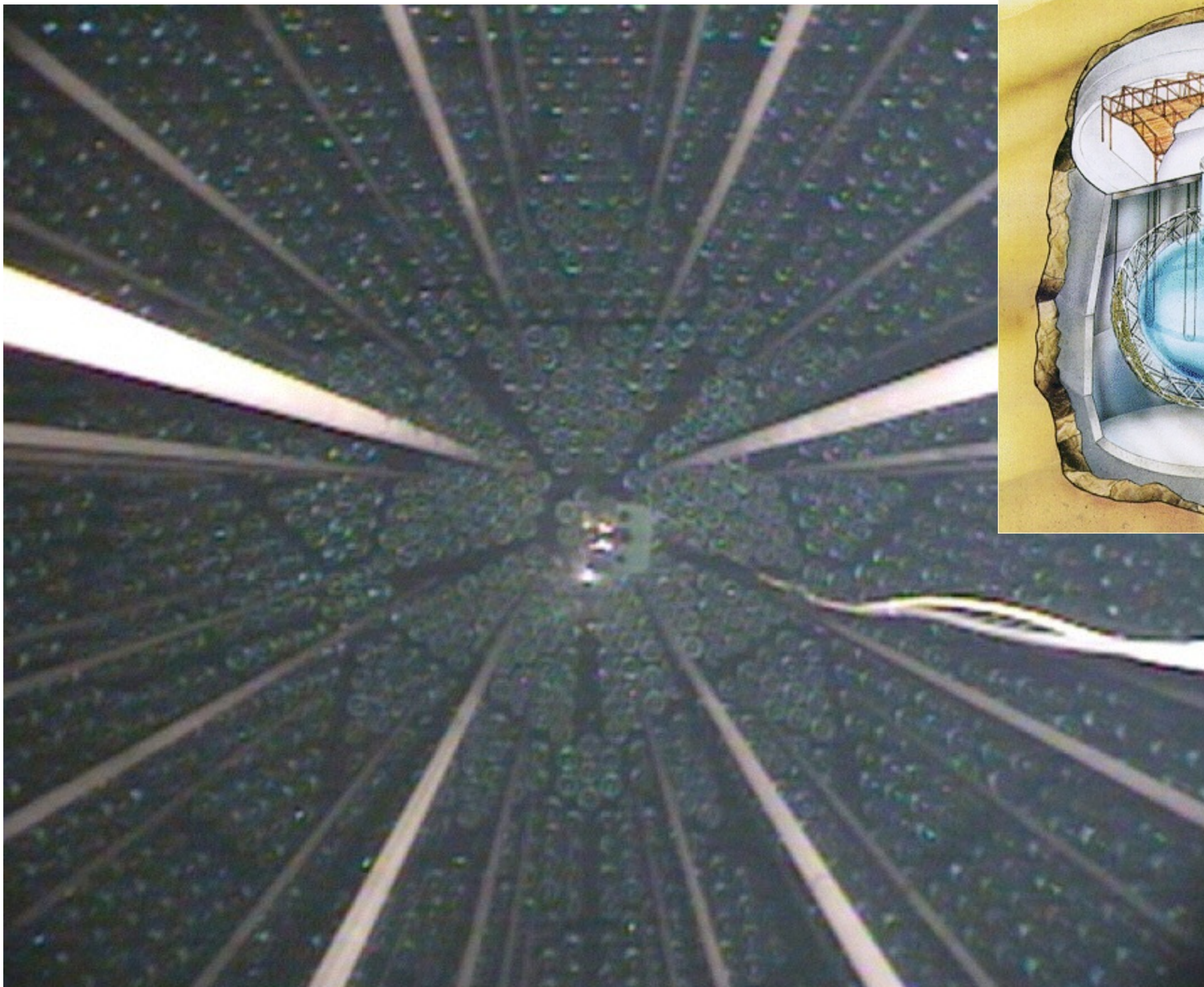
Nov. 04 - Nov. 06

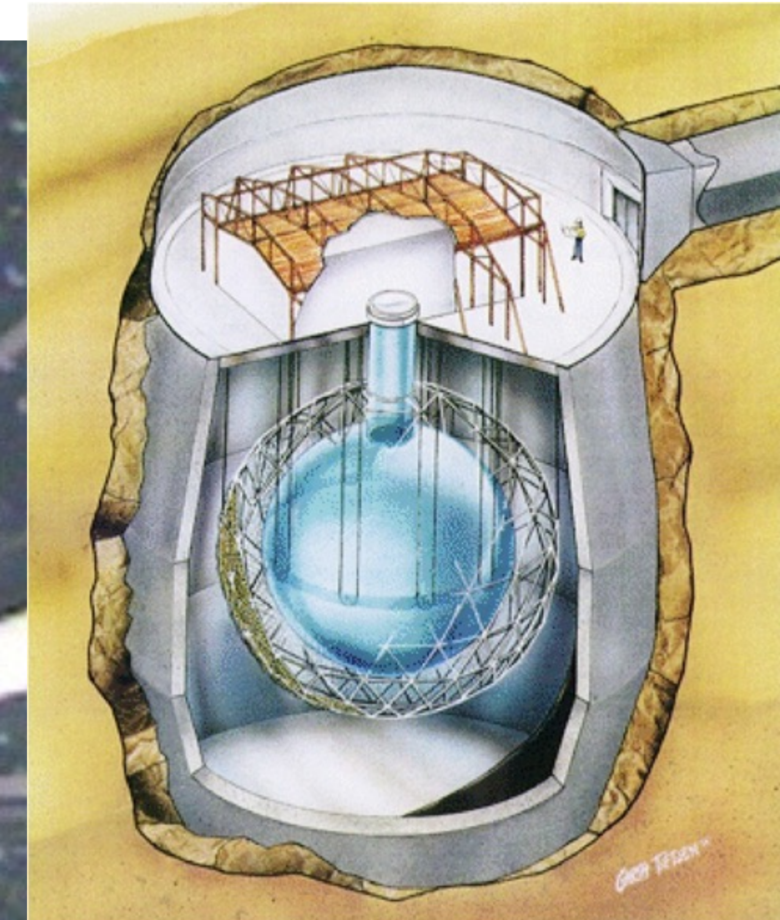
40 proportional counters
$^{3}He(n, p)^{3}H$
σ = 5330 b
Observe p and ^{3}H
PC independent readout
Event by Event Det.



$$n + {}^{3}He \rightarrow p + {}^{3}H$$

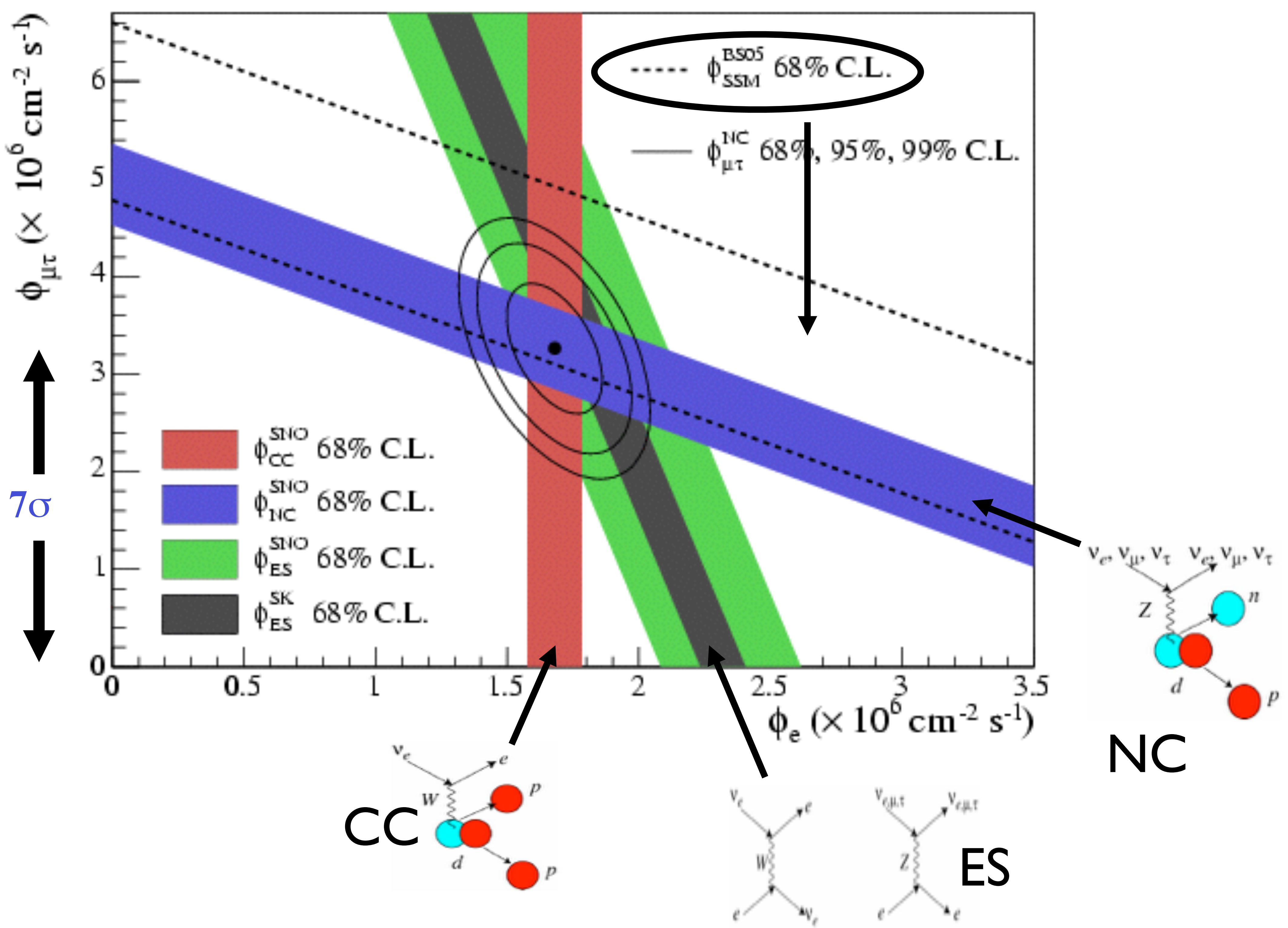
The SNO NCD Array





Salt Flux Measurements

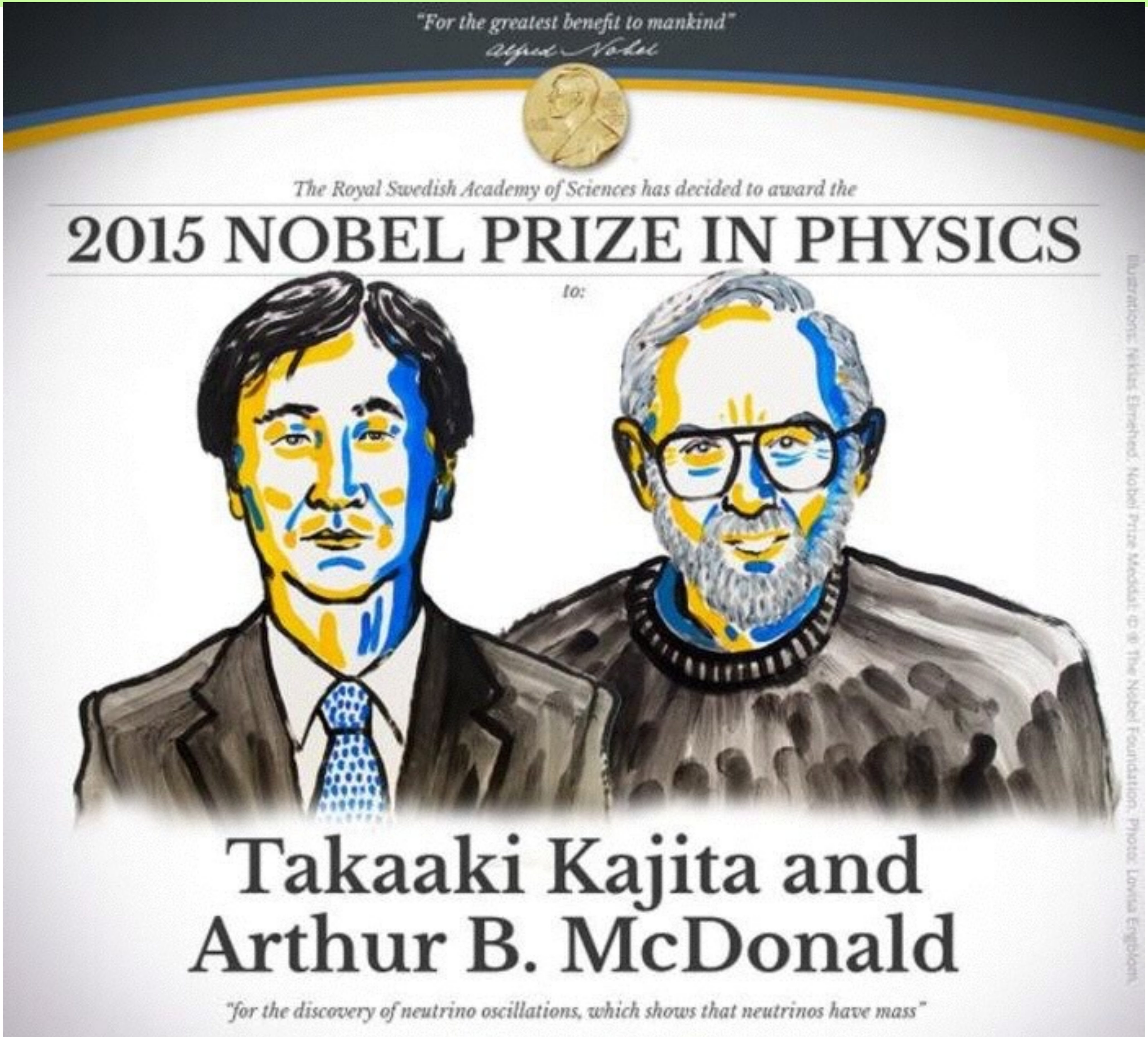
SNO Collaboration, PRC 72, 055502 (2005)
391 Days of Dissolved Salt Data



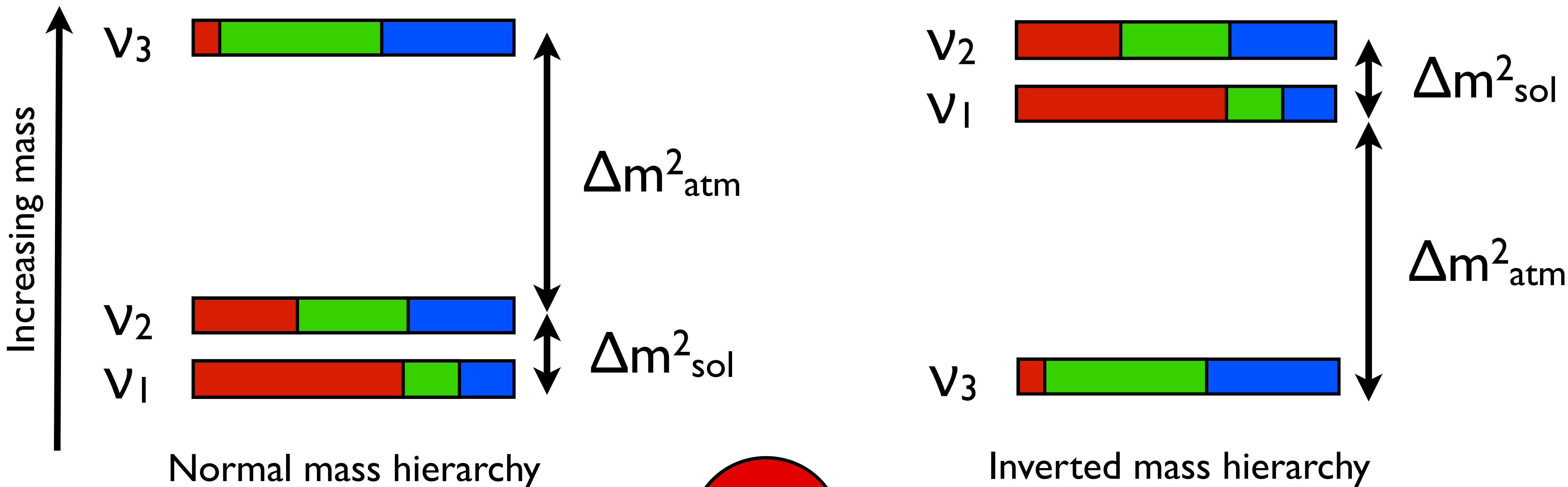
Los Alamos and SNO

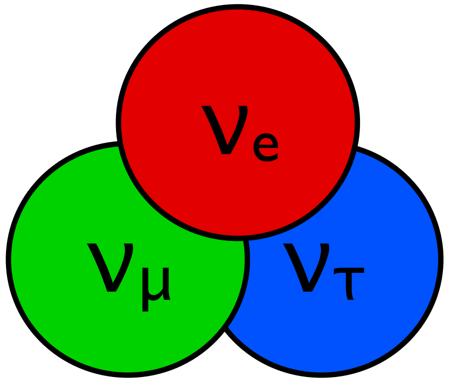
- LANL had several major roles in SNO:
  - Procured all 10,000 low-background photomultiplier tubes (also used in LSND)
  - Provided custom calibration sources
  - Significant R&D for the NCD development
  - Led analysis of the salt and NCD phases
  - Role in the data acquisition software
  - Involved in a number of simulations
- Over 10% of SNO collaborators worked at Los Alamos at some point during the project

Nobel Prize in 2015!



Neutrino Oscillations





- Neutrino flavor change: oscillate between mass eigenstates -- implies neutrinos have mass
- Solar, atmospheric, and reactor neutrino measurements give differences between eigenstates but not absolute value or order

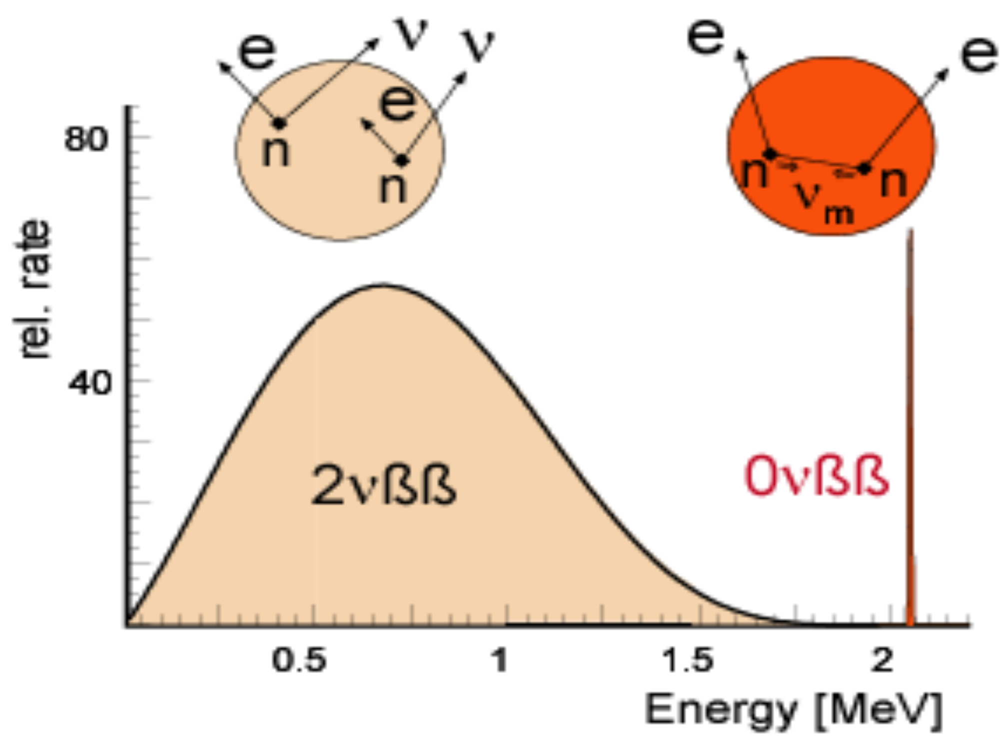
What's next for neutrinos?

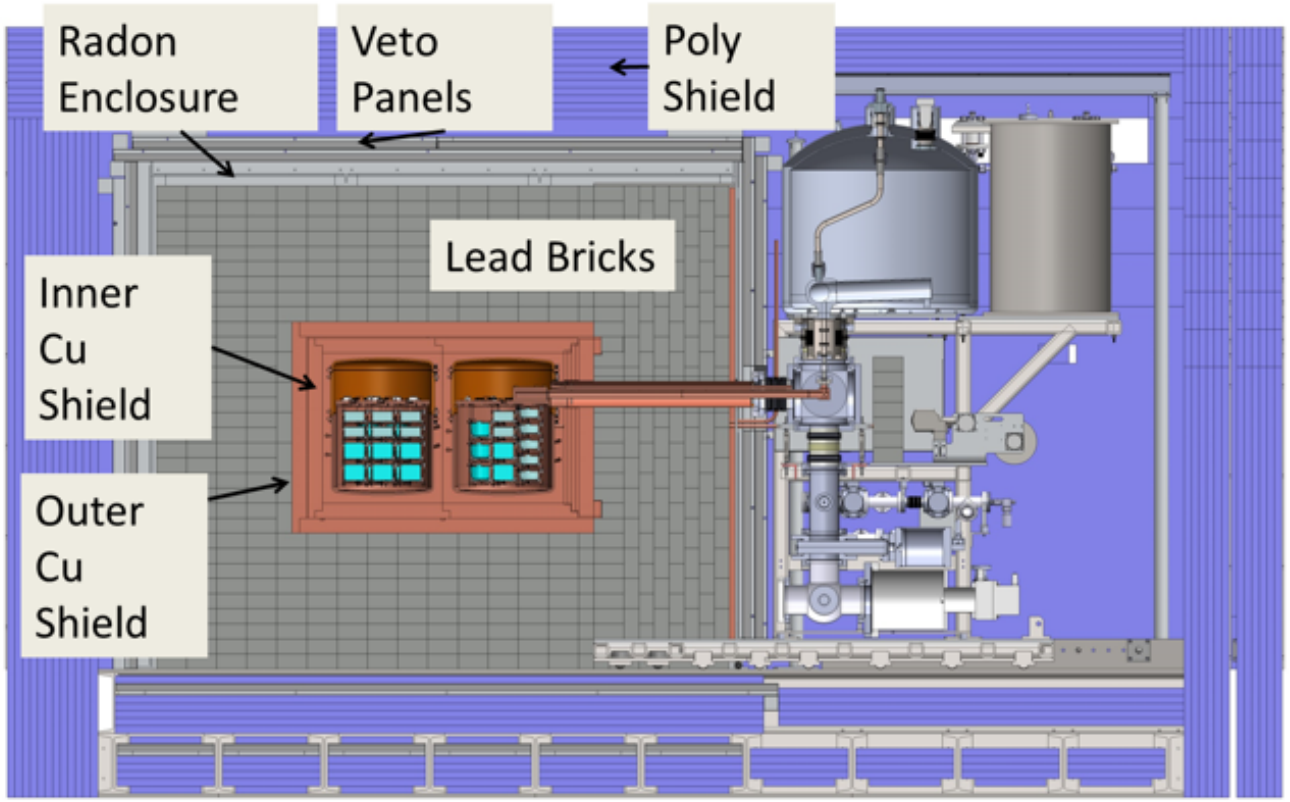
Current/Future

- What is absolute mass?
  - Beta and double beta decay experiments
- What is the mass hierarchy?
  - Long baseline accelerator neutrinos
- Are neutrinos their own antiparticles?
  - Double beta decay experiments
- Is there a CP-symmetry violation? Differences in neutrino vs. anti-neutrino oscillations
  - Long baseline accelerator neutrinos
- Are there non-active neutrino types (sterile neutrinos)?
  - Short baseline accelerator neutrinos, hot source experiments

Double Beta Decay Experiments

Current/Future



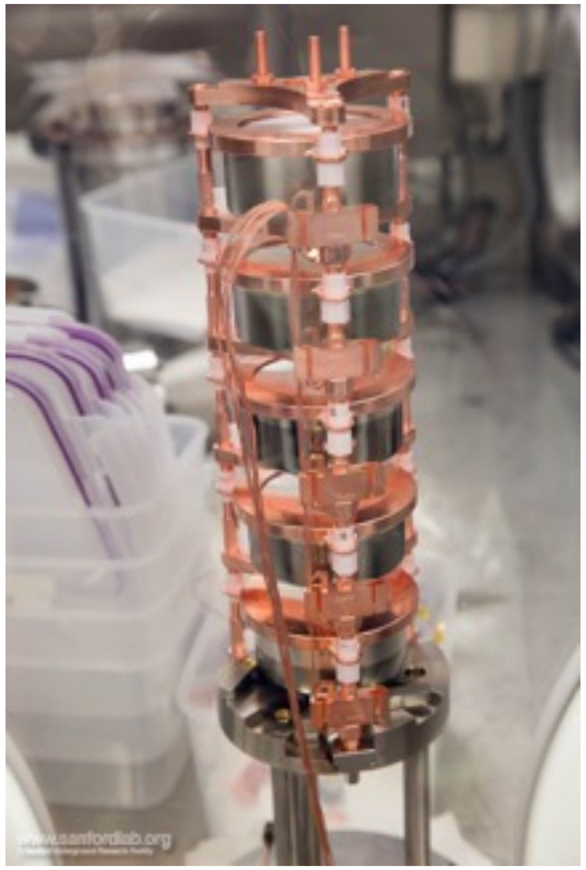


Neutrinoless double beta decay experiments searching for process that has half-life $>10^{28}$ years

If observed, will show that neutrinos Majorana in nature and can determine effective mass

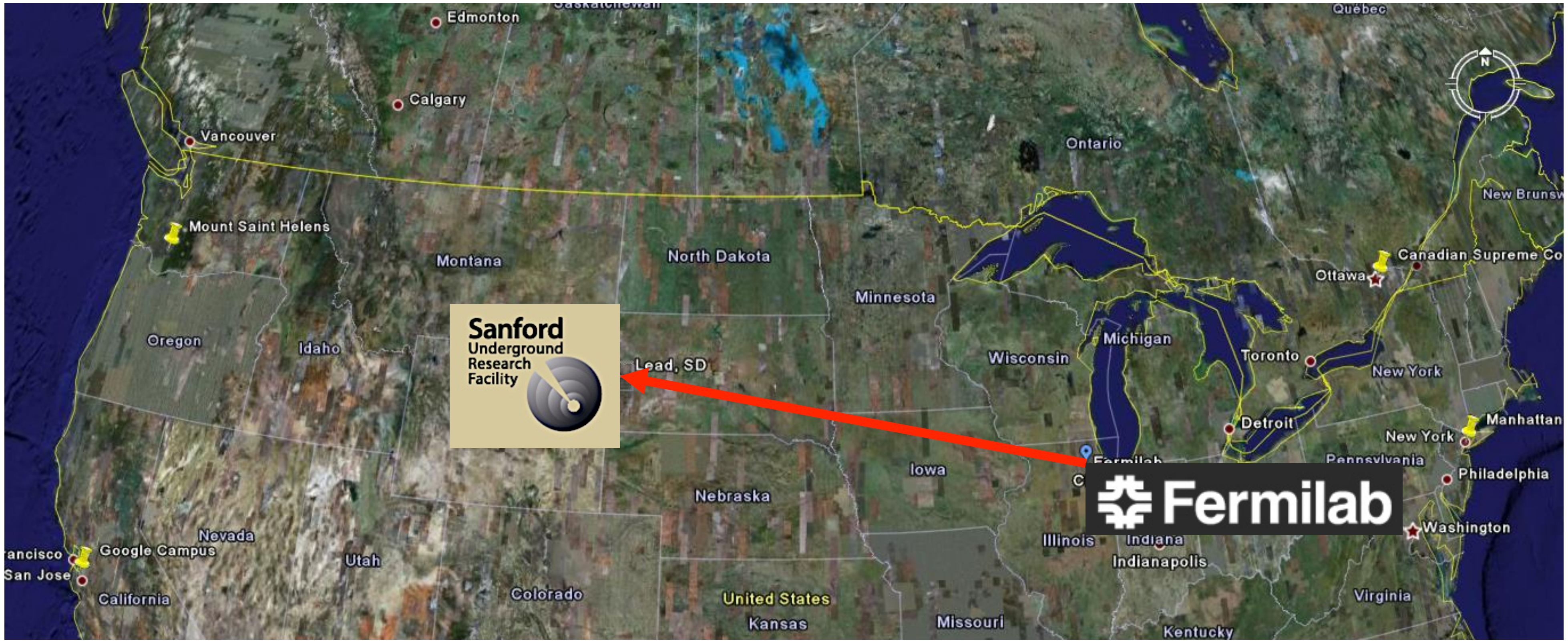
Double Beta Decay Experiments

- The MAJORANA DEMONSTRATOR is a current double beta decay experiment at the Sanford Underground Research Facility in SD
  - Utilizes enriched Germanium detectors as both source and detector
  - Los Alamos provided detectors, shielding, calibrations, infrastructure, simulations, and analysis
- Developing a next generation experiment with an international collaboration capable of reaching the inverted hierarchy



DUNE/LBNF

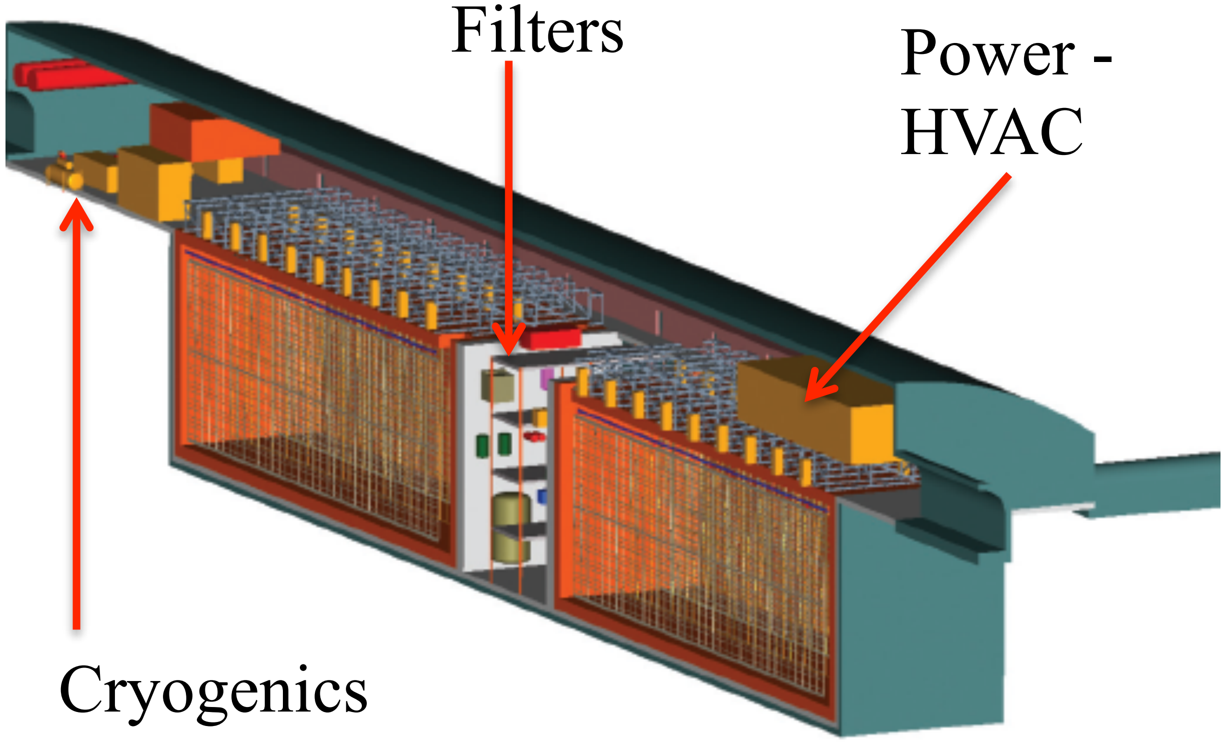
Current/Future



Program consists of:

- an intense beam of neutrinos from Fermilab
- near detector systems at Fermilab
- a 40 kt liquid argon time projection chamber at Sanford Underground Research Facility at 4850’

DUNE/LBNF



Far detector:

- Four 10 kt modules
- TPCs capable of tracking the resulting shower from neutrino interactions

Will search for:

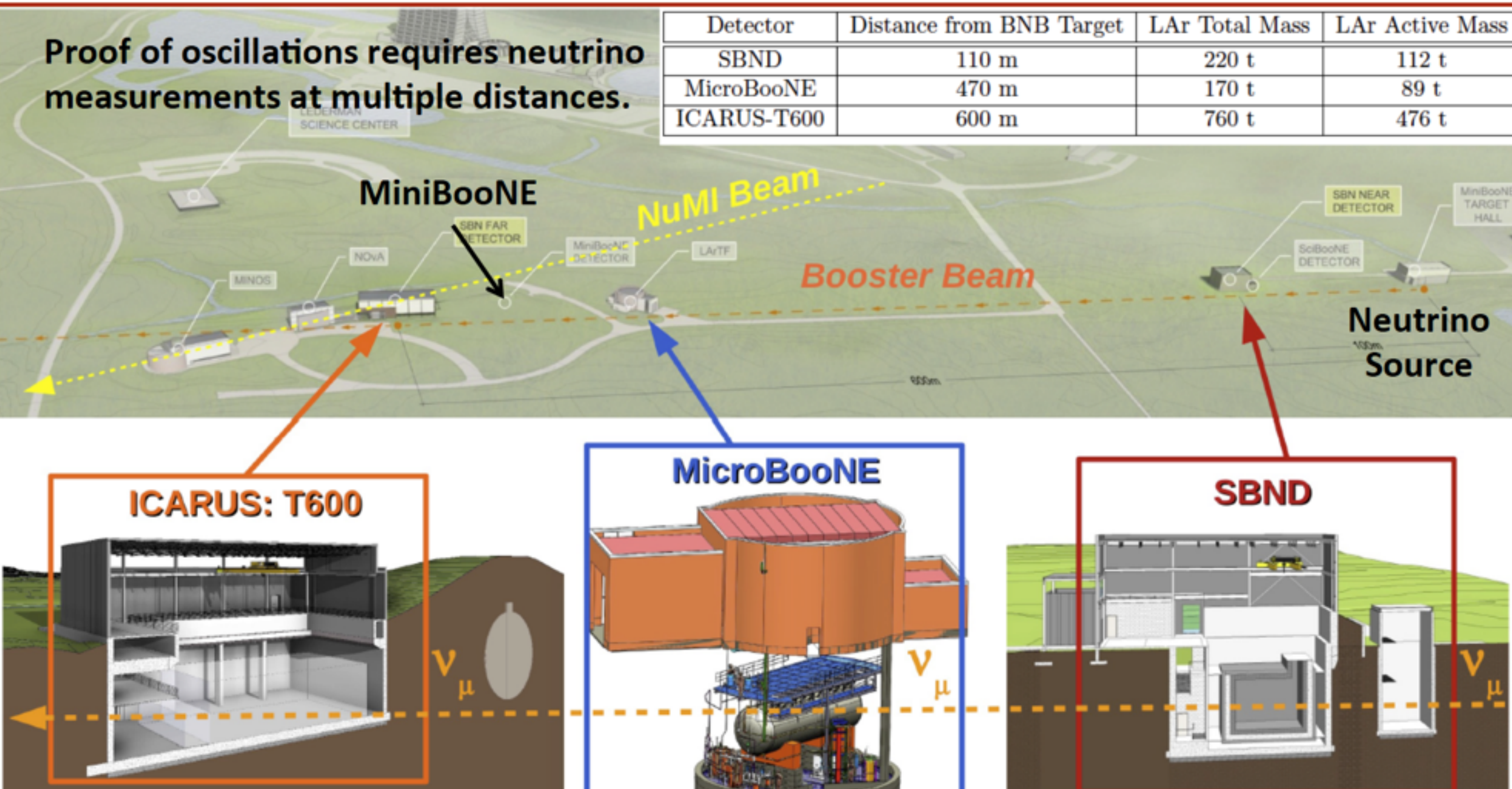
- Neutrino oscillation physics with neutrinos and antineutrinos — look for asymmetry, hierarchy
- Proton decay
- Supernova neutrinos

Los Alamos is studying neutron interactions in liquid argon with Mini-CAPTAIN at LANSCE

Short Baseline Accelerator Neutrinos

Current/Future

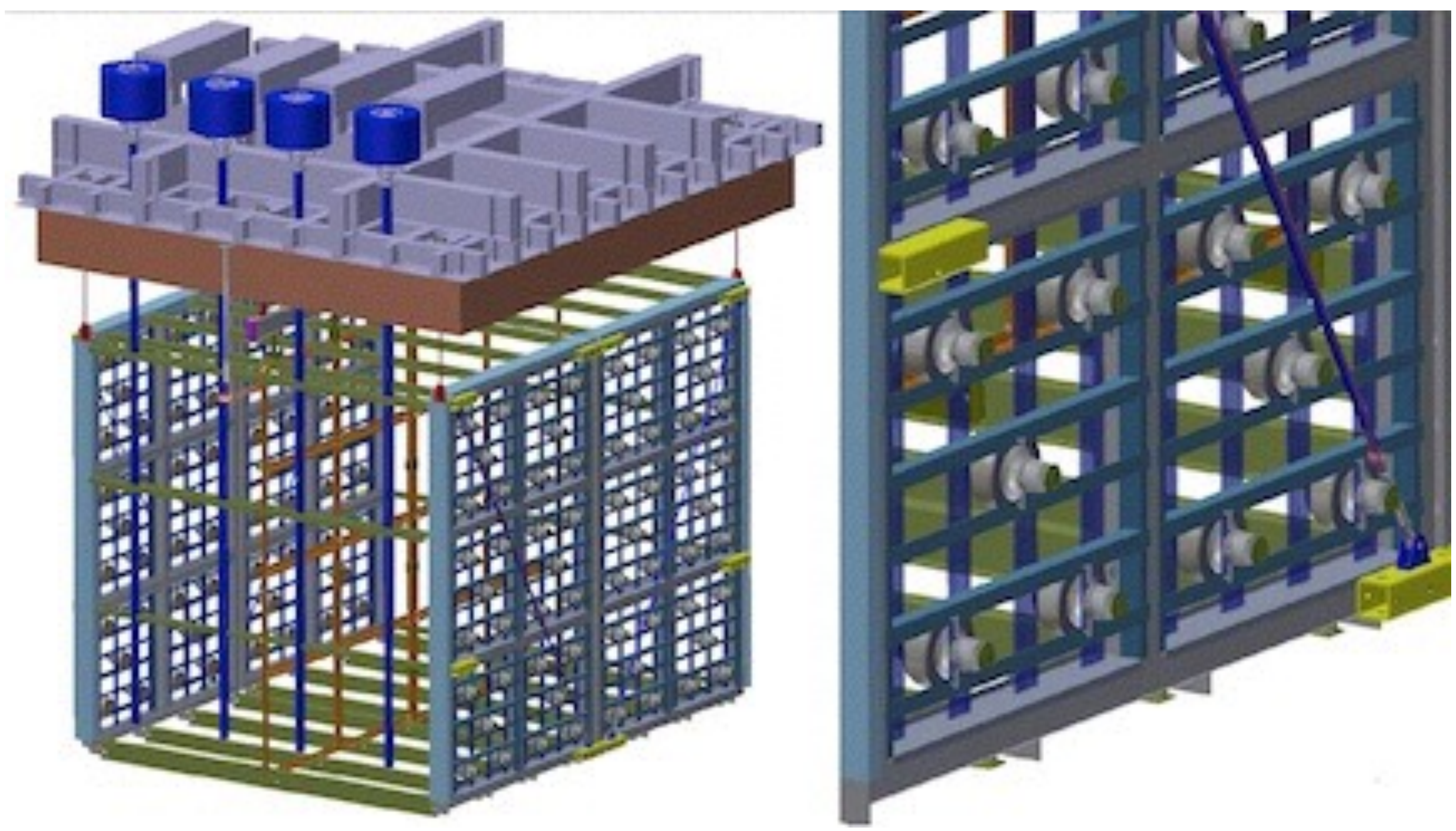
Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
SBND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS-T600	600 m	760 t	476 t



Short baseline program at Fermilab trying to resolve oscillation anomalies that suggest a much heavier sterile neutrino

Short Baseline Accelerator Neutrinos

- Los Alamos is part of all three detectors: Short Baseline Near Detector, MicroBooNE, and ICARUS
- Providing the photon detection system for SBND
- Goal is to determine if there are sterile neutrinos and answer the LSND result



Summary

- Los Alamos has played a central role in the neutrino story
- From the discovery in 1956 …

  to historic measurements at LAMPF,

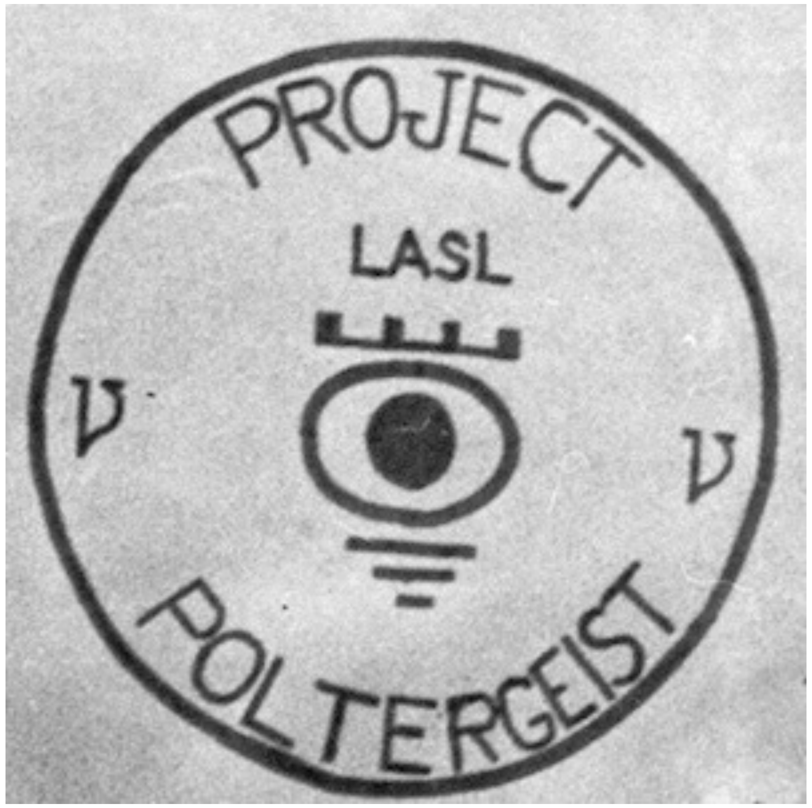
  to helping solve the Solar Neutrino Problem,

  to providing possible evidence of a sterile neutrino,

  to searching for its mass with beta and double beta decay
- The future holds more excitement as this "elusive Poltergeist" continues to slowly reveal its secrets

Many thanks!

- Thanks to everyone at Los Alamos (past and present) who has worked in the field of neutrinos
- And those who helped with this talk in particular:
  Gerry Garvey, Hamish Robertson, Steve Elliott, Bill Louis, and Allan Carr (Lab Historian)



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- *LANL Image Library* - images.lanl.gov